VTT

E3 Pandemic Response

Final Report

Jaakko Paasi (Ed.)

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Preface

The E3 Excellence in Pandemic Response and Enterprise Solutions project was launched in 2021 as a response to the COVID-19 pandemic. The ambitious goal of the project was to develop solutions that allow various functions of society to continue uninterrupted and people to continue to move and live safely despite the epidemics and pandemics. The project, often called using its short names ‘E3 Pandemic Response’ or just ‘E3’, had a multidisciplinary approach combining seven Finnish research institutes and 22 forerunner companies in different branches of science and industry. Details of the project consortium are given in the Introduction chapter of the report.

This report is a compilation of the main results of the project. It includes full papers and extended abstracts from the research done. Many of these works have been published or will be published elsewhere in more detail. The idea of this report has not been to collect all the findings and development work done in the project together but to have one report where the main results of the project are presented. Furthermore, the style of writing was instructed to be such that experts in any field represented in the project could understand (at least to some extent) all the papers in the report.

The E3 project was supported by Business Finland, with a total budget of 12 M€ during the years 2021-2024, being one of the largest co-innovation projects ever funded by Business Finland. The project consortium expresses thanks to Business Finland for the support. In particular, we would like to thank Maarit Lahtonen for her contribution to the project steering.

I would like to thank the members of Editorial board (Arto Säämänen & Aku Karvinen at VTT Technical Research Centre of Finland, Tarja Sironen at University of Helsinki, Eija Asmi & Hilkka Timonen at Finnish Meteorological Institute, Enni Sanmark at Helsinki University Hospital HUS, Piia Sormunen at Tampere University, Jutta Kannisto & Jari Erkkilä at Tamlink, Markku Heino at Spinverse) for your efforts in designing this E3 Final Report. All the Editorial board members had also an important role in leading the project work as work package or use-case leaders or in the project coordination.

Last, but not least, I would like to thank Aimo Taipale for his contribution to the ideation and design of the E3 Excellence in Pandemic Response and Enterprise

Solutions project. Without Aimo's impact, the project would not have been as successful as it was.

COVID-19 has been stated to be over as a pandemic, but new epidemics and pandemics will come sooner or later. The authors of the report hope that the E3 work would have an impact on improving the economic and societal resilience of our nation to face future epidemics and pandemics.

Tampere, October 1, 2024

Jaakko Paasi
Chief Editor

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1 Introduction

1.1 Overview of the E3 Excellence in Pandemic Response and Enterprise Solutions co-innovation project

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Abstract: E3 Excellence in Pandemic Response and Enterprise Solutions (E3) project was launched in 2021 to address the need for resilient solutions to mitigate the impact of pandemics. By combining expertise from 22 Finnish companies and 7 research institutes, the E3 project harnessed modern science and technology to create effective countermeasures to prevent the spreading of infectious diseases. The project's findings build a new comprehensive understanding of airborne transmission of pathogens, offering solutions and a basis for future pandemic preparedness.

1.1.1 Introduction

The E3 Excellence in Pandemic Response and Enterprise Solutions (E3) co-innovation project was launched in 2021, as a response to the global COVID-19 pandemic. It was built based on three previous co-creation projects: AIRCO (Air transmission control of COVID-19), L2B (License to Breath), and TUPA (Scientifically studied safety concepts for the mitigation of the societal effects of the pandemic), which all were funded by Business Finland.

The COVID-19 pandemic exposed the vulnerabilities within our societies and global economies, highlighting the need for improved resilience against global health crises and increased understanding of such infectious diseases. The pandemic impacted societies at all levels, from individuals to states and international organizations and from small companies to large international business ecosystems. It changed the world and, for instance, the ways of communication, transportation, use of office buildings, health care and care of elderly people. The pandemic had a huge negative impact globally. As of

September 2024, it has caused 7.06 million deaths and 776 million reported infected (WHO, 2024), many of whom suffered severe illness. Additionally, the restrictions and reduced social contacts caused mental health issues, challenged the education system with remote learning methods, cancelled cultural events and caused vast economic damage across multiple sectors.

In addition to these serious consequences caused by the disease, the airborne transmission route was one of the biggest challenges. As evidence accumulated during the COVID-19 pandemic, it became increasingly clear that airborne transmission plays a significant role in the spread of infectious diseases. It meant that the disease was also spreading through the air, by droplets and small aerosol particles emitted when infected people were breathing, talking, coughing, and sneezing.

The E3 Pandemic Response and Enterprise Solutions co-innovation project was designed to respond to these challenges, aiming to deepen the understanding of the different pathways of pathogens and viruses are spreading, especially the airborne transmission, but also virus control and detection methods, while simultaneously developing innovative, scientifically validated solutions for mitigating the spread of such infectious disease, particularly in indoor environments. The main goal was to develop solutions that allow the various functions of society to continue uninterrupted and people to continue to move and live safely despite epidemics and pandemics.

The research and development work conducted in the E3 project has been groundbreaking, combining many fields of research expertise and forerunner companies to lay the groundwork together for a better and more resilient future.

As such, the E3 is one of the largest co-innovation projects ever funded by Business Finland, with joint targets by 22 companies and 7 research institutes and a total budget of 12 M€ during the years 2021-2024.

1.1.2 A multidisciplinary approach is needed to tackle pandemics

The COVID-19 pandemic demonstrated that diversity of countermeasures is the key to fighting pandemics. No single measure, regardless of its effectiveness, can fully control a pandemic on its own. Thus, the E3 project was built around the need for a comprehensive, multidisciplinary approach that brought together experts from various fields, including medicine, engineering, environmental science, behavioural science, and business innovation. A crucial part of the E3 project was the involvement of Finnish high-tech companies, who partnered with the research to share their expertise and to develop new kinds of solutions. Without the companies' involvement, the E3 project could not have reached its objective to develop scientifically sound but also commercially viable solutions, products and services.

The E3 project consortium consisted of multidisciplinary research from Finnish research organizations:

- medicine (Helsinki University Hospital, HUS)
- microbiology (University of Helsinki, UH; Finnish Institute for Health and Welfare, THL)
- aerosol physics and technology (Tampere University, TAU; VTT Technical Research Centre of Finland, VTT; Finnish Meteorological Institute, FMI),
- smart buildings (TAU, VTT)
- industry technology (Tampere University of Applied Sciences, TAMK)
- business models (TAU, VTT)
- behavioural science (THL, Finnish Institute of Occupational Health, TTL)

The companies in the E3 project with their own R&D projects included AFRY Finland Oy, EG Finland Oy, Granlund Oy, Helsinki University Hospital (HUS), Halton Oy, Lifa-Air Oy, Inspector Sec Oy, Vetrospace Oy, Filterpak Oy, and Rune & Berg Design Oy.

With in-kind contributions from Air0 Oy, Airlyse Oy, Alme Solutions Oy, AW2 Architects Oy, Biomensio Oy, Cleamix Oy, Kone Oyj, Lumikko Oy, Olfactomics Oy, Ramboll Finland Oy, Roche Diagnostics Oy and Royal Caribbean Group.

The E3 project was built with the support of two innovation ecosystems, the Indoor Air Quality ecosystem (IAQe) and CleverHealth Network. The E3 project is coordinated by Tamlink Oy and Spinverse Oy.

1.1.3 Research focus of the E3 project

The joint research plan of the E3 project consisted of six major research themes, interlinked closely with each other as well as with the projects of individual companies. In addition, the research results were utilized in practice in three use cases focusing on socially significant interiors.

The research themes of the E3 project were:

- Risk assessment, Prevention & Control strategies
- Pathogens & Human beings
- Emissions, Dispersion, Deposition & Exposure
- Detection & Monitoring & Diagnostics
- Airborne Contamination Control
- Integration of Indoor Concepts & Solutions

The research results from the abovementioned were utilized in three different use cases:

- Smart Modular Healthcare with hospital pilots in Romania and Finland
- Smart Office & Micro-climate solutions
- Daycare intervention in four daycares based in Helsinki

The main research questions covered scientific, technological and business perspectives and underlined the importance of the multidisciplinary approach of the project:

1. How epidemic diseases spread in the indoor environment? What is the relative importance of different disease transmission modes?
2. What are effective countermeasures and their development needs?
3. How are the countermeasures turned to new global business?

The E3 project has made significant advancements in understanding virus transmission, infection mechanisms, and airborne contaminants. The next chapters will introduce the major results and findings of different research areas of the E3 project and summarize key conclusions.

1.1.4 References

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1.2 Overview to E3 research and E3 Final Report

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Abstract: This paper gives an overview to the research done in the E3 Pandemic Response project by presenting the overall approach of the research, main research questions of the project, and the overall content of the chapters in this E3 Final report, where answers to the main research questions are given.

1.2.1 Introduction

The COVID-19 pandemic showed how vulnerable societies all over the world are against pandemics. Our societies were not sufficiently well prepared against this kind of pandemic. One reason for the unpreparedness is that the last great lethal global pandemic, which really affected people's everyday life, was the Spanish Flu one hundred years ago. It is typically crises that triggers major changes in societies. The calm period of one hundred years without a lethal global pandemic may also have let us to lull into a false sense of safety, although there has been severe local epidemics such as SARS or West African Ebola.

Before the COVID-19, pandemic preparedness was largely based on influenza viruses and the knowledge of their transmission. The global COVID-19 pandemic showed the inadequacy of this approach. Furthermore, COVID-19 revealed that the modes and mechanisms of transmission routes of different viruses are poorly understood and debated, leading to great challenges for the stakeholders to define necessary and efficient restrictions. Shortages of understanding were clearly one reason why our societies were almost closed during the hardest weeks of COVID-19. The pandemic preparedness before COVID-19 neither took into account possibilities that modern technology could offer in mitigating the spread of pathogens.

Controlling the spreading of pandemics, requires a comprehensive approach to cover all relevant transmission routes. No single countermeasure, such as vaccinations, helps enough alone. It is important to consider the whole chain from pre-cautionary actions, like restrictions, to spreading, diagnosis and tracking. The countermeasures must be addressed to the correct stage of the chain.

During the first year of COVID-19 pandemic, more and more evidence was accumulated confirming that airborne transmission plays an important role in the spreading of SARS-CoV-2 viruses. It was also found that asymptomatic people may infect several others without even understanding the risk and that some people may act as superspreaders infecting several others at the same time. These findings had a major impact to the formation and content of E3 Pandemic Response project. The project become multidisciplinary where different specialists, like medical doctors and engineers, seeks to fill in knowledge gaps on

the molecular features and transmission of pandemic viruses and find the most efficient measures for active intervention in different parts of the society.

1.2.2 Main research questions of E3 Pandemic Response project

When designing the E3 Pandemic Response project, it was obvious that, at one day, COVID-19 will be over as a pandemic (although the SARS-CoV-2 virus causing the pandemic may continue spreading in the planet). Therefore, the target of the project was to go beyond COVID-19 in improving economic and societal resilience to face future epidemics and pandemics.

The main research questions of the multidisciplinary E3 Pandemic Response project cover scientific, technological, and business perspectives and underline the importance of the multidisciplinary approach of the project:

1. How epidemic diseases spread in the indoor environment? What is the relative importance of different disease transmission modes?
2. What are effective countermeasures and their development needs?
3. How are the countermeasures turned to new global business?

Answers to the main research questions were searched under the project structure described in the previous paper (chapter 1.1). It is worth to note that the main research questions were not specific to a particular work package (WP) of the project but guided the work of several WPs. In accordance, the papers in this E3 Final Report are not organized according to the WP where the main work was done. Instead, the organization is done thematically.

None of the main research question was not answered comprehensively, although lots of important findings and valuable conclusions could be derived based on the research done in the project. The main research questions were further specified through (sub) research questions that are presented in the papers of this E3 Final report.

During the COVID-19 pandemics there was a huge market demand for solutions mitigating the spread of SARS-CoV-2 viruses, solutions that have been scientifically proved. When the pandemic was announced to be over, the market demand collapsed. People (including businesspeople as well as consumers) found other interests than mitigating the spread of pathogens. That forced us in the E3 project to do some changes in our research plans. The business-oriented main research question ‘How are the countermeasures turned to new global business?’ still remained, but its focus was broadened beyond SARS-CoV-2 to cover any pathogens for whom airborne transmission route play an important role in the spread of pathogen. In the research it was also admitted that the market need may have to be created by the research arguments of E3 project results.

1.2.3 Overview on chapters of E3 Final Report

Papers in E3 Final Report consist of full papers describing work that has not (yet) been published in scientific journals and extended abstracts of works where a peer-reviewed scientific article is available or will be shortly available. In these cases, a DOI of the scientific article, if available, is given in the extended abstract for readers who would like to read the results of subject in more detail. The style of writing in both full papers and extended abstracts takes into account the multidisciplinary nature of E3 Pandemic Response project. They have been written in a way that experts in any of the research disciplines in the project should understand, at least to some depth, all the papers in the report.

The content of the report is arranged so that it starts from virology and studies virus and aerosol generation and survival in Chapter 2 and moves then to studies of virus and aerosol detection in Chapter 3. Virus and aerosol go here hand-in-hand because in air transmission of viruses, the viruses always need an aerosol particle to act as a carrier. Chapter 4 then focuses on deepening our understanding on the flow of air in different indoor conditions. This research harnessed recent developments in computational fluid dynamics to serve the project goals.

The research in these three chapters is more or less guided by the 'scientific' research questions: how epidemic diseases spread in the indoor environment, and what is the relative importance of different disease transmission modes? They form scientific basis for research guided by the other main research questions: what are effective countermeasures and their development needs, and how are the countermeasures turned to new global business?

In countermeasures aiming to mitigate the spread of pathogens and being infected by the pathogen it is a question of risk management. When effective, the probability of being infected is essentially lowered. Countermeasures hardly ever reach to complete block the pathogen transmission. Chapter 5 presents the work done in the E3 project for the calculation and controlling the transmission risk of microbia.

In the remaining chapters of the report, the research has been brought into buildings and rooms inside the buildings, each chapter giving a specific standpoint for the research questions 2 and 3.

Chapters 6 and 7 form an entity that considers technology, human and market aspects of health-safe buildings with a special focus on smart offices. 'Smart' means here application of technological solutions in mitigating the spread of pathogens in indoor environments of building. While the research in Chapter 6 is more on a building level, Chapter 7 searches possibilities to create micro-environments with improved indoor air quality in specified small spaces inside rooms.

The last two chapters report on real interventions done in the project. The first one, Chapter 8, present main findings on work done in improving the indoor air quality in hospital environments. Interventions were done in two different types of hospitals: in a modern hospital with mechanical ventilation in Helsinki, Finland and

in a traditional naturally ventilated hospital building in Bucharest, Romania. Chapter 9 then reports findings on interventions done in four daycare centres in Helsinki, Finland, where air purification devices were installed to purify the room air. The technological countermeasure to mitigate the spread of viruses was linked with clinical research to study the morbidity of children in the daycares. According to our knowledge, this was the first time when medical and technological research have been joined together to study the impact of purified indoor air to the morbidity of people against infectious diseases.

Chapter 9 also includes perhaps the most important research result of the project. In the daycare centres, where the air was cleaned with air purifiers, children's morbidity decreased by 18 percent. The significant 18 percent reduction was achieved without implementing other infection mitigation strategies beyond air purification. The finding highlights growing scientific evidence that common respiratory infections are spread through the air.

Finally, industrial benefits of the E3 Pandemic Response project are discussed in Chapter 10 as concluding remarks of the E3 Final Report.

The chapters are arranged so that, at first, there will an introductory paper which directs readers into the topics of the chapter and gives motivation and background for the research done. Some of these introductory papers give also overall conclusions of the chapter. The introductory paper is then followed by the specific full papers and extended abstracts under the theme of the chapter.

2 Aerosol and virus generation and survival

2.1 Animal models to study transmission routes and to estimate the viral doses

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Abstract: This work was done to set up a disease model for Covid19. In order to study the pathology of the disease and conditions such as long covid, a more advanced animal model is needed. Animal model was also needed to define the routes of transmission the virus takes to spread as well as the infectious doses. We were able to produce SARS-CoV-2 in mink and show that the virus is transmitted through aerosols.

2.1.1 Introduction

To understand infectious diseases in humans and animals and to develop vaccines, special attention should be focused on selecting an appropriate animal model. Suitable animal model depends not only on the pathogen you are studying but also the research question and it should mimic the situation in humans as closely as possible. For example, studying vaccine response might need a different animal model than studying transmission of the same virus. In addition to the biological aspects, ethics, cost, and availability affect decision making.

In SARS-CoV-2 research, hamsters, mice, ferrets, and non-human primates have been used as animal models; each having their own advantages and

limitations. Mice have been commonly used to study a number of infectious diseases. However, mice lack the receptor required for SARS-CoV-2 entry into host cells, which is why alternative strategies, including genetically modified mice, have been developed. Syrian hamsters have been commonly used because they are naturally infected and develop a clinical disease resembling that of humans (Bi et al., 2021). They have also been used in SARS-CoV-2 transmission studies and both aerosol and fomite transmission has been shown (Port et al., 2021). However, non-experimentally infected hamsters have shown milder clinical signs, suggesting that hamster may not be the perfect animal model to study SARS-CoV-2 transmission (Bi et al., 2021).

Non-human primates are commonly used to study vaccine response and the infection is generally mild-to-moderate. However, high requirements when it comes to expertise and facilities when handling primates makes it non-optimal animal model. Ferret is also naturally infected with SARS-CoV-2 and develops a generally mild disease. The virus is efficiently spread between ferrets which is why it has been used to study transmission routes of SARS-CoV-2 (Bi et al., 2021).

In addition to the species mentioned above, SARS-CoV-2 is known to naturally infect numerous other animal species. A prominent example is American mink (*Neogale vison*), and the virus has been detected in both farmed and feral mink in multiple countries. This has led to extensive environmental contamination and human-to-mink and mink-to-human transmission. These factors caused strict measures in mink-farming countries to prevent the spread of the disease. Due to the outbreaks, the European Centre for Disease Prevention and Control and the WHO have highlighted the importance of studying the host-animal interface to recognize new threatening variants.

In addition to the natural infections, American mink has been suggested as a good animal model for COVID-19 due to the clinical picture resembling that of humans. However, more information was needed to determine its applicability for studying virus transmission (Bi et al., 2021).

In addition to virus transmission, determining the infectious dose can be even more challenging. I review on SARS-CoV-2 transmission detected significant variability in the infectious dose depending on the animal model and experimental design (SeyedAlinaghi et al., 2022).

More information with different species is needed to understand the applicability of each animal model. The aim of this project was to study American mink as an animal model for SARS-CoV-2 and its transmission.

2.1.2 Method/Research design/Experimental

Two animal experiments on mink were conducted during this research. In the first experiment 20 mink (ten male and ten female) were used. Out of these, six were vaccinated against COVID-19 and four were unvaccinated. The mink were infected by intranasal exposure using 8x10^5 viruses of the alpha variant of SARS-CoV-2. The animals were anesthetized and sampled for blood before infection. The condition and signs of disease in the mink was observed daily by

qualified animal caretakers. The animals were sampled by collecting saliva daily until euthanization seven days post-infection. Blood samples were drawn at termination. Stool samples were also collected daily to determine whether this sample material could be used for monitoring possible exposure to the virus.

In the second experiment the response of American mink to SARS-CoV-2 was tested by infecting three male and two female mink intranasally with the Omicron variant. Two uninfected mink of each gender were included to study virus transmission. All the mink were in separated by 10-20 cm gaps (Figure 1). The mink had no physical contact but were housed in open, wireframe cages.

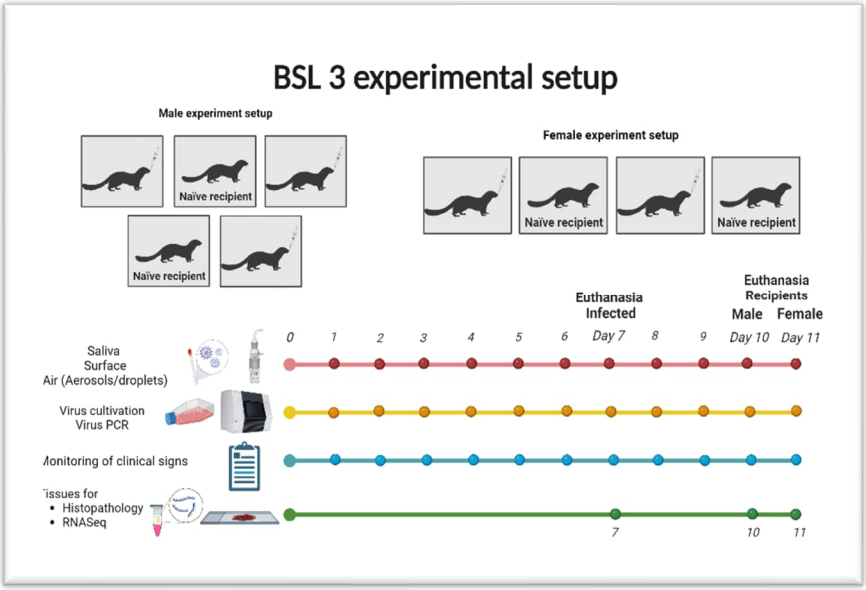

Figure 1. Experimental setup for transmission experiment of SARS-CoV2 omicron in mink.

A follow-up on infected mink was conducted for seven days (infected mink) or ten days (uninfected mink). Sampling of saliva, assessment of clinical signs, serum sampling, and histopathologic evaluation of upper and lower respiratory tracts was done on each animal. The saliva was sampled daily and tested for the presence of both viral RNA and viable virus. Environmental samples were also collected from air, personal protective gear, and surfaces. Aerosol samples were collected by the Bio Sampler with 5 ml Cell culture media and 30-minute sampling time.

2.1.3 Results/Findings

All experimentally infected mink showed mild to moderate signs of illness, including lethargy, anorexia, diarrhea, discharge from the eyes and nose, and sneezing and/or coughing. Saliva samples from the directly infected animals tested PCR-positive the first day postinfection (dpi) and remained that way throughout follow-up in both experiments (Virtanen et al., 2022). Infectious virus was cultured 1–3 dpi. Even though some of the clinical signs could be caused by other factors, such as stress from the change of environment, their consistency with signs seen in other studies, combined with PCR results, demonstrate clinical disease in mink. This indicates that the infectious dose used was correct as it resulted in moderate signs and a slowly developing disease.

Similar signs to the experimentally infected mink developed in both sets of uninfected recipient mink, and they were consistently PCR-positive from 3 dpi onward, indicating mink-to-mink transmission through air. Infectious virus was detectable by cell culture before it was detected by PCR. They also developed clinical signs similar to the infected mink although they were already asymptomatic at euthanasia.

Pathology findings in the nasal cavity and lungs were subtle in both experimentally infected and recipient mink and consisted of hyperemia of respiratory mucosa with small amounts of viscous exudate and noncollapsed, dark-red, and wet pulmonary lobes. All mink showed histopathologic changes in the upper and lower respiratory tracts. We observed multifocal degeneration and loss of respiratory epithelium with variable mucosal and submucosal neutrophilic infiltration in the nose. Viral nucleoprotein was widely distributed beyond intact cells, within sloughed cells, and in mucosal respiratory epithelium. Unlike in some experimental infections reported in rodents, clear pathology was observed in the lungs enforcing the role of mink in pathogenesis studies. In 2 inoculated and both recipient mink, pulmonary lesions were associated with viral antigen expression and characterized by multifocal to coalescing alveolar damage with degeneration or necrosis of alveolar septa, infrequent hyalin membrane formation, and variable proliferation of type II pneumocytes. This indicates that the method of infection can be used to produce close to that happening naturally but that recipient animals could be used to further study mechanics of the disease. The virus could also be found in the brains of some infected animals suggesting possible animal model for long-covid.

Further analysis is ongoing, but preliminary results show that the virus was captured in the aerosol collections and was able to grow on cells. The histological results also seem to be in line throughout the experiments independent of the virus strain.

2.1.4 Conclusions

The results show that SARS-CoV2 can spread effectively through aerosols. It also shows that timing the sampling is of utmost importance. As we compare the results to earlier attempts to isolate live virus from hospital ward (Oksanen et al., 2022), we can confidently say that the sampling for SARS-CoV-2 transmission studies needs to be done before or at the early onset on visible symptoms. This means that aerosol surveillance of public spaces could be a viable option in monitoring viruses and protecting public health. As such monitoring could also be done through PCR, it would make this all the more useful.

On animal models, we can recommend mink as a viable addition to rodents in studying SARS-CoV-2. It develops very similar clinical signs and histological responses as humans do. Most interesting was the finding of the virus in the brains. This would warrant a longer follow up study to see whether the mink would develop long term signs and could therefore be used in the study of long covid. The infectious dose used was 800 000 cfu per animal and produced a steadily advancing infection using both alpha and omicron strains.

When comparing different strains, Omicron, which is currently the dominant variant, is somewhat different from the other variants. It spreads more efficiently, primarily attributable to immune escape and likely milder symptoms in humans. This study shows that mink can be infected by Omicron and, crucially, efficiently transmit the virus to other mink despite the reports of lower virulence.

2.1.5 Acknowledgements

The team would like to thank The Helsinki University large animal facility for expert assistance in the care of the animals. We would also like to thank the Finnish fur breeders association for help in obtaining the animals.

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2.2 Microbial aerosol sampling and infectivity under different environmental conditions

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Abstract: This study explores the infectivity of microbial aerosols in different relative humidity (RH) conditions and the suitability of different microbial aerosol samplers for the detection of different microbes. The RH was found to affect the infectivity of enveloped model virus Phi6 aerosol dramatically, while used bacterial aerosol was quite oblivious to the change in RH. Non-enveloped MS2 model virus was also affected by the RH, but less than Phi6.

2.2.1 Background

Airborne transmission is a key mode of spreading infectious diseases such as SARS-CoV-2, measles, chickenpox, and influenza. The COVID-19 pandemic led to a rethinking of the distinction between aerosol and droplet transmission. Instead of classifying particles based on size, any inhalable particles are now referred to as aerosols, acknowledging that respiratory particles from an infected person vary in size. However, the difference between short-range transmission (via larger particles that settle quickly) and long-range transmission (via smaller particles that remain airborne) is still recognized, though both are mitigated through similar measures like masks and social distancing. Particle size matters for other control tools like ventilation and air purification, and it is also relevant when collecting bioaerosols to study infectious agents.

Effective bioaerosol collection methods are essential to understanding airborne pathogens and assessing the effectiveness of countermeasures. Bioaerosols can be collected using various methods, such as filtration and impaction, and then analyzed for microbial presence. These approaches allow for the accurate identification and quantification of pathogens, as well as determining their viability or infectivity. There are many different bioaerosol collection devices and a variety of different measurement techniques, such as qPCR, DNA/RNA sequencing, and cultivation-based methods, each with its own strengths and limitations.

This study aimed to address the lack of comparative analysis between different bioaerosol sampling methods. In a controlled chamber, we compared various microbial aerosol sampling techniques and assessed their effectiveness for quantifying different microbes. We also examined how relative humidity affects sampling success and the infectivity of bacterial and viral targets. Our work

contributes to improved preparedness for monitoring pathogens in future infectious disease outbreaks.

2.2.2 Methods

The measurements were done in a sealed 30 m^3 stainless steel walled chamber. The chamber was equipped with a fan to ensure efficient mixing of the airspace. The temperature and relative humidity were monitored, and the temperature was kept between 22.1°C and 24.6°C.

Three microbial aerosol samplers were used: a six-stage Andersen cascade impactor, a BioSampler (SKC Inc, USA), and a BioSpot (Aerosol Devices, USA). All were based on inertial collection, functioning as impactors (Andersen) or impingers (BioSampler and BioSpot). The BioSpot uses supersaturated water vapor to grow particles into larger droplets for gentle and more efficient collection. The Andersen impactor collected samples on an agar plate, while the BioSampler and BioSpot collected them in Peptone-saline solution. The Andersen impactor had cut-off diameters ranging from 7 µm to 0.65 µm across its stages. The BioSampler had a cut-off of 0.5 µm, and the BioSpot's cut-off was below 10 nm. Flow rates were 28.3 l/min for the Andersen, 12.5 l/min for the BioSampler, and 8 l/min for the BioSpot.

The study involved four microbes: *Bacillus atrophaeus* (dormant spores), *Staphylococcus warneri* (active bacteria), and two viruses, MS2 (non-enveloped) and Phi6 (enveloped), representing a range of microbial properties.

Test runs followed a consistent protocol. The chamber was flushed with HEPA-filtered air to reduce background particles. After conditioning the chamber to the desired relative humidity, a test aerosol was introduced via a pneumatic atomizer for 7 minutes. Samples were taken at 0, 15, 30, 45, 75, and 120 minutes with 3-minute sampling time. The particle size distribution was monitored throughout the experiment.

Nutrient agar (NA) plates were used with Andersen impactor. After sampling, the NA plates were incubated, and colonies were counted. The collection liquid (5 ml from BioSampler and 3 ml from BioSpot) containing collected microbes were diluted and cultured (viruses were first combined with their host bacteria) on NA plates, incubated and colonies or plaques were counted.

2.2.3 Results

We did not observe a significant loss of infective airborne particles compared to the overall depositional loss of aerosol particles with any of the microbes studied at RH 20% during the 120 min experiment. At RH 60%, there was a 3 $\log_{10}$ loss of infective MS2 containing particles during the 120 min experiment, and the same 3 $\log_{10}$ loss was observed with Phi6 already after 45 min, after which we did not observe any infective airborne Phi6 in the chamber air (Figure 1). At RH 80%, Phi6 stayed infective for longer, and 3 $\log_{10}$ loss of infective Phi6 particles was observed during the 120 min experiment. The bacterial aerosol was quite oblivious

to the changes in RH. We also observed that the concentration of virus containing aerosol was significantly lower in the initial 0 min sample at RH 20% than it was under more humid conditions. This prompt inactivation of viruses in dry conditions before collecting the 0 min sample accounted for more than 90% of the total loss of infective virus particles. The normalized concentrations of infective virus aerosols during the 120 min experiment in different RH conditions are presented in Figure 1. The normalization was done by dividing the concentration of each sample by the corresponding 0 min sample from the same experiment run to make the results comparable despite the differences in the initial microbial particle concentration.

We found notable difference in the collection efficiencies among the samplers. The BioSampler generally performed better collecting bacteria than viruses, whereas the BioSpot performed better collecting viruses than bacteria. The difference in collection efficiencies was most notable while collecting Phi6 viruses, as sometimes we did not collect any infective viruses with BioSampler, while BioSpot was collecting well detectable amounts. Interestingly, the difference in collection efficiencies between the two sampling devices was much smaller for bacteriophage MS2. The Andersen impactor was by far the most sensitive sampling device, as it collected the microbial aerosol directly onto an agar plate without diluting the sample. If the agar plates contain the host bacteria, it is also possible to collect the viruses directly onto the plate. We managed to do this with Phi6, but not with MS2.

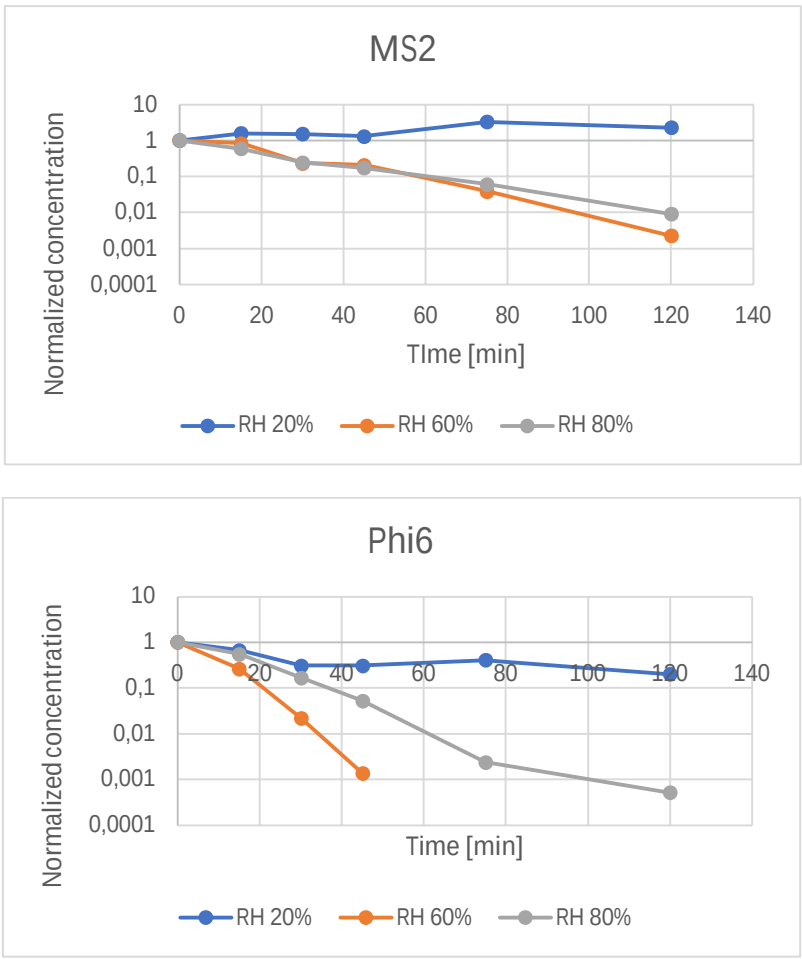

Figure 1. The time evolution of infective virus aerosol for MS2 (top panel) and Phi6 (bottom panel). Samples were collected with BioSpot.

2.2.4 Discussion and conclusions

The effect of RH on the infectivity of viruses has been observed before (Morris et al. 2021). The effect is more notable for enveloped than non-enveloped viruses, as we saw also in our experiments. We are confident, that the RH related behavior is due to the hygroscopic properties of salts in the solution, from which the microbe containing particle is produced. In our case, the salt was mostly NaCl, which has an efflorescence RH of 42% and deliquescence RH of 75%. Below efflorescence RH the particle is dry, and above deliquescence RH it is a droplet. Between efflorescence and deliquescence RH the particle is a droplet, given that it has initially been a droplet and never experienced an RH lower than efflorescence RH.

As we atomized the microbial aerosol from a liquid solution, at 60% RH in our experiments, the particle is a droplet, and in a metastable state in supersaturated solution with respect of NaCl. We believe that this metastable state is the cause of the sudden loss of infectivity of viruses.

The loss of collection efficiency in BioSampler seem to be related to the harsh conditions in the sampler, where the sampled air is accelerated to the speed of sound and the contained particles are impacted against a liquid surface. This is supported by the finding that the collection efficiency is higher for MS2 than Phi6. The size of both viruses is well below the cut-off diameter of the BioSampler, which means that the sampled particles are carried in a larger particle or droplet, so that not much difference based on the actual size difference is expected.

In BioSpot the particles are also impacted against a liquid surface, but at much lower velocity than in the BioSampler. Furthermore, the particles are grown into droplets, and the microbes within may experience some protection from the liquid envelope. Still, the result is that the sampling conditions are not nearly as harsh as in a BioSampler, which results in an improved collection efficiency for sensitive enveloped viruses. However, the consequence of having a better collection efficiency for viruses comes at the expense of having a poorer collection efficiency for bacteria. The bacteria are relatively large, and while experiencing the supersaturated water vapor conditions of the BioSpot, they grow into droplets large enough to experience increasing depositional losses.

Increasing the humidity above the deliquescence RH of NaCl may help to terminate the airborne transmission route of some viruses, even when considering the prompt loss of infective virus aerosol when droplets dry out at low RH. The viruses surviving the transmission through the metastable stage to dry aerosol phase seem to stay infective for a long time, whereas the viruses lingering in the metastable stage lose their infectivity rapidly over time.

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2.3 Bioinformatic characterization of ENPEP, the gene encoding a potential cofactor for SARS-CoV-2 infection

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EXTENDED ABSTRACT

2.3.1 Background

The coronavirus disease 2019 (COVID-19) pandemic, caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), has led to extensive research on the mechanisms by which the coronavirus can enter the body and infect human cells. SARS-CoV-2 shares similarities with SARS-CoV, the virus which caused the previous SARS epidemic in 2002–2004, including the use of ACE2 as a viral receptor. However, COVID-19 is more transmissible and variable in severity. Differences in the spike (S) protein, such as a novel furin cleavage site, contribute to these variations.

Previous studies revealed low ACE2 expression in the lung, contrary to first expectations, with higher expression in other organs such as the small intestine and kidney (Barker & Parkkila, 2020). This challenged preconceptions about SARS-CoV-2 tissue tropism. Neuropilin 1 (NRP1) enhances viral entry by acting on the S1/S2 cleavage site (Cantuti-Castelvetri et al. 2020). Other molecules, such as cathepsin L, CD147, and kidney injury molecule 1 (KIM1), may also facilitate SARS-CoV-2 entry.

Other auxiliary proteins or even potential coreceptors include aminopeptidase N (APN encoded by the ANPEP gene), glutamyl aminopeptidase/aminopeptidase A (APA encoded by the ENPEP gene), and dipeptidyl peptidase 4 (DPP4) on the basis of their coexpression with ACE2, and the roles of APN and DPP4 as known coronavirus receptors for HCoV-229E and MERS-CoV, respectively.

APA is a zinc metalloenzyme involved in cleaving peptides such as angiotensin 2. APA and ACE2 are closely related in the renin–angiotensin–aldosterone system (RAAS), a key mechanism of blood pressure regulation. Present in several tissues, such as the small intestine, kidney, liver, brain, and vasculature, APA has been suggested to play a part in diseases such as cancer and renal dysfunction. Despite gaps in knowledge about the role of APA in some organs, its strong correlation with ACE2 suggests that it may be a coreceptor or cofactor for SARS-CoV-2 infection (Barker & Parkkila, 2020). Our research aimed to elucidate the distribution and function of APA via bioinformatic approaches.

2.3.2 Methods

The present study used several bioinformatics methods and public datasets to analyze the expression, transcriptional regulation, and role of the ENPEP gene and the corresponding protein product, APA. The datasets included the Genotype-Tissue Expression (GTEx) project, MSigDB database, the Human Protein Atlas, the HeRA database, and the Ensembl database. scRNA-Seq expression count data were obtained from several comprehensive tissue-specific analyses hosted on the CellxGene Discover platform. These datasets included the Human Brain Cell Atlas v1.0, Heart Cell Atlas V2, Gut Cell Atlas, and the Human Lung Cell Atlas.

2.3.3 Results

ENPEP mRNA is highly expressed in the small intestine and kidney cortex, with lower levels in tissues such as visceral adipose, coronary arteries, lung, and spleen. Immunohistochemical staining revealed strong APA signals in the small intestine and kidney, which correlated with mRNA expression.

Single-cell RNA-Seq data revealed high ENPEP expression in small intestine enterocytes, kidney proximal tubular cells, liver hepatocytes, and brain excitatory neurons. Smooth muscle cells in various tissues, particularly vasculature, also presented significant ENPEP expression, likely indicating ENPEP expression in blood vessel-associated pericytes.

ENPEP mRNA expression did not significantly vary with age in the lung, intestine, or kidney. However, differences were observed in some tissues, such as skeletal muscle, prostate, and liver. ENPEP expression also significantly overlapped between sexes, with no systematic increase in expression in either males or females.

ENPEP expression strongly correlated with the expression of genes related to angiogenesis, such as NRP1, ADGRL4, and VEGFC. In gene ontology analysis, ENPEP was most highly associated with the function and development of the circulatory system, with the five most significant ontologies being ‘blood vessel morphogenesis’, ‘blood vessel development’, ‘vasculature development’, ‘cardiovascular system development’, and ‘circulatory system development’. Terms related to endothelial function and chemotaxis were also identified.

The prediction of transcription factor-binding sites in the promoter region of the ENPEP gene identified a FOX family TF cluster upstream of the ENPEP gene, which aligns with enrichment analysis results showing strong associations with STAT3, STAT5B, and FOXD3 target genes.

2.3.4 Discussion and conclusions

Our results demonstrate that ENPEP and ACE2, the gene encoding the SARS-CoV-2 viral receptor are strongly correlated in the small intestine and renal cortex.

In addition to tissue specific expression, ENPEP is also expressed in pericytes and vascular smooth muscle cells across a variety of organs. In the lung, ENPEP is also most prevalently expressed in alveolar wall fibroblasts closely associated with vasculature. This vascular expression of ENPEP is also a possible area of overlap with ACE2, the SARS-CoV-2 receptor, which has been shown to be present in these vascular pericytes.

ENPEP and ACE2 could also be involved in similar biological processes beyond the regulation of blood pressure, particularly angiogenesis. The ENPEP gene is also strongly correlated with genes known to be related to angiogenesis and vascular function, such as NRP1, ADGRL4, and VEGFC. Gene ontology analysis of ENPEP linked the gene to biological processes related to angiogenesis, including blood vessel morphogenesis and cardiovascular development, with similar findings in our previous study of ACE2. Further linking the two, ENPEP and ACE2 appear to have a stronger correlation than many of the other genes associated with SARS-CoV-2, such as TMPRSS2, CTSL, and NRP1 both overall and in blood vessels.

Previous studies have associated APA with diseases such as cancer and dysfunction, and APA expression appears to be upregulated in tissues that undergo induced angiogenesis, such as in tumors and inflamed tissues. Systemic inflammation such as in SARS-CoV-2 could also serve toupregulate the ENPEP gene.

Our research suggests that APA may function as a cofactor for SARS-CoV-2 entry at the cellular level. The distinct vascular expression of ENPEP, especially in pericytes, may contribute to COVID-19 pathology, including vascular inflammation and blood–brain barrier disruption. The role of ENPEP in RAS/RAAS may also impact disease severity by influencing ANG2 and ANG3 levels.

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2.4 A pilot study of aerosolization of infectious murine norovirus in an experimental setup

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EXTENDED ABSTRACT

2.4.1 Background

Noroviruses cause approximately 700 million infections globally per year. They spread mainly by faecal-oral route and transmit via food, water, or contact with fomites, such as common-touch surfaces. Norovirus causes mainly acute diarrhoea and vomiting. Reports of disease outbreaks in which other transmission routes than airborne have been unlikely, have been published (Sawyer et al., 1988). So far, airborne transmission of noroviruses has not been much studied.

Commonly used model for human norovirus is murine norovirus that structurally resembles human norovirus. Murine norovirus can be cultivated to high numbers in a continuous cell line, whereas cultivation of human noroviruses is extremely challenging in laboratory. Both viruses have an RNA genome that is inside of a small protein shell, but they don't have an outer lipid envelope (non-enveloped viruses).

Norovirus is quite stable in the environment as compared to many other viruses. Demonstration of infectious viruses in the indoor air is still challenging, although only infectious virus can cause disease. Demonstrating presence of viral genome in the air does not reveal if the virus is infectious or damaged.

Aim of this pilot study was to establish a simple aerosolization system which could enable experiments using infectious murine norovirus in aerosols. Among the few earlier publications, Alsved et al. (2020) has reported aerosolization studies using murine norovirus, MNV.

2.4.2 Methods

A small 3-l air-chamber system was used for virus aerosolization. First, we placed an open dish, containing cells in which the virus can grow as well as cell culture solution, into the air chamber. A solution containing a high concentration of viruses

(6 $\log_{10}$ MNV $TCID_{50}$/ml; median tissue culture infectious dose) was implemented to generate aerosols into the chamber air. Solution was collected from the dishes after the aerosol exposure time of 30 min or 90 min. We also followed the virus growth on the exposed cell-containing dishes. After the exposure, we determined the concentration of infectious virus from all those samples (Mosselhy et al., 2022).

2.4.3 Results

We could demonstrate the presence of infectious murine noroviruses in the aerosols in the chamber air. All the details of the study can be found in the publication (Purhonen et al., 2024).

The measurements confirmed the presence of high numbers of aerosol particles in the air inside the glass chamber. This number of aerosol particles contained virus particles and other particles from the original virus solution.

We observed that the original virus used for aerosol generation in the air chamber preserved well its viability throughout both exposure times. Especially, the virus loads at the start remained reproducible in all experiments.

We observed virus growth on the exposed cell dishes after all experiments. In addition, murine norovirus preserved infectivity in the solution taken from the dish after each aerosol exposure. The infectious virus loads for the 90-min samples were close to three times the result from the 30-min experiments. However, the infectious virus concentrations in the samples taken from the air chamber were several ten-folds lower than the concentration of the original virus solution.

2.4.4 Discussion and conclusions

We could establish a simple aerosolization system that can be used to study the behaviour of infectious viruses when aerosolized in the laboratory. Detection of infectious viruses in indoor air aerosols is challenging. In this study, we found that the traditional cell culture method for MNV worked well in an experimental setup. The setup can be used to generate more data and increase our understanding on how environmental conditions affect the infectivity of aerosolized viruses.

This study, performed using a model virus for human norovirus, increased our experience in handling aerosolized non-enveloped viruses. Norovirus has the benefit of being very stable in the environment and this characteristic may be useful in the establishment of the system in comparison to less resistant enveloped viruses. It may also reveal some aspects that can help us understand the fate of aerosolized respiratory viruses, such as SARS-CoV-2.

A high-titre virus was used when aerosols were generated, in line with most studies. In some real-world situations, such as during vomiting, high numbers of noroviruses can be aerosolized temporarily in addition to droplets. Workers in wastewater treatment plants may also be exposed to high levels of viruses and other microbes aerosolized in air.

However, infectious virus loads were clearly low or lower in the air chamber, which hardly renders them detectable in the viability test techniques currently used in indoor air. So far, we have lacked techniques sensitive enough to detect infectious virus levels in air under real-world conditions (Oksanen et al., 2022). Future efforts should focus on developing these sensitive techniques.

In conclusion, we showed that MNV could be aerosolized and that viruses remained infectious for some time in the experimental setup used. Thus, it can be used for more detailed studies.

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3 Aerosol and virus detection

3.1 Challenges related to airborne pathogen measurements

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Abstract: Recently, largely due to COVID-19 epidemy, the scientific community has realized that airborne pathogens may have an important role in the spreading of several diseases. However, measuring the airborne pathogens, with size ranging from nano- to micrometers, is extremely challenging. In addition to small size of pathogens, challenges in measurements include 1) lack of suitable collection devices for airborne pathogens, 2) lack of sensitive and selective detection method(s) for various different pathogen types, 3) lack of ability to identify the pathogen from the mixture of harmless and harmful airborne particles, 4) lack of information about the sources of pathogens, 5) lack of information related to dilution, and spreading of pathogens after emission. Furthermore, as various types of technologies and sampling protocols are used for collection of pathogens, comparability of the results from different devices is often poor. As a result, currently the pathogen emissions, dispersion modes, and infectivity or viability of viruses and other microorganisms found in atmospheric aerosol droplets are poorly understood (e.g. Wang et al., 2021) regarding safety procedures and recommendations worldwide. A better understanding of each of these processes related to atmospheric spread of diseases, combined with an analysis of the pathogen removal such as deposition mechanisms of viruses in droplets and small aerosol particles would be crucial to prevent airborne spread of viruses and other harmful microorganisms and to decrease the probability for new infections. This kind of knowledge and information could be applied both in directing human social behavior and movement patterns and in the development of technical systems that keep e.g., indoor environments safe.

To address this, we need to develop research capacities (devices, detectors, knowhow) and infrastructures (e.g. ability to produce micro-organisms in laboratory, calibration systems, intercomparison studies) to build the competence and better

serve the current and future research needs for emissions, dispersion, deposition, and exposure of airborne pathogens and other micro-organisms. This chapter describes the state-of-the-art regarding aerosol and microbe generation, collection and detection and highlights the gaps in the knowledge.

3.1.1 Current challenges in studies related to airborne pathogens

In the pre-COVID era respiratory infections were assumed to spread mainly by droplet and direct contact routes. However, as evidence piled up on the long-distance transmission in different occasions the airborne transmission route was also recognised as a probable transmission path. Currently for the Covid-19 airborne virus spreading is acknowledged, even by WHO. This has created a strong pressure to characterize the airborne pathogens as well as their spatio-temporal variation and significance.

One major reason for the uncertainty in assessing the importance of airborne transmission is the difficulty of determining airborne virus levels. This is related, on the one hand, to the fast spatiotemporal variation of pathogen concentrations in indoor settings and, on the other hand, on the challenges in the sampling and analysis of the viruses.

The emission rate of pathogens is a key factor in estimating airborne concentration levels and thereby inhalation infection risk. This depends on activity affecting the emission rate of exhaled droplets and the pathogen concentration contained in these droplets. The latter varies over time peaking shortly after infection and then declining steadily (Killingley et al., 2022), The viral load of SARS-CoV-2 in respiratory fluids of an infected person can vary hugely from <10^4 to over 10^11 RNA copies per milliliter. It is obvious that this variability adds complexity to the measurement and interpretation of results.

On the sampling and analysis side there are several challenges:

- **Detection Sensitivity**: Airborne viruses are typically present at very low concentrations, requiring large sample volumes and highly sensitive detection methods to identify and quantify them accurately.
- **Sampling Efficiency**: Collecting airborne viruses without losing a significant portion during the sampling process is difficult. Various collection methods, such as filters, impingers, and electrostatic samplers, have different efficiencies and can affect the integrity and viability of the collected viruses.
- **Environmental Conditions**: Factors such as temperature, humidity, and air flow can impact both the survival of airborne viruses and the effectiveness of sampling equipment. Viruses may degrade or lose infectivity under unfavorable environmental conditions, complicating accurate measurement.
- **Interference from Other Particles**: The air contains numerous other particles (e.g., dust, pollen, bacteria) that can interfere with the detection and quantification of viruses which needs effective differentiation between various microbes.
- **Bioaerosol Viability**: Maintaining the viability of viruses during sampling and transport is essential for certain detection methods, such as culture-

based assays. However, the physical stresses and environmental conditions during sampling, transport and storage can reduce the viability of viruses.

- **Analytical Methods**: Different analytical techniques have been employed for detection and quantification of SARS-CoV-2, such as reverse transcription-polymerase chain reaction (RT-PCR), droplet-digital PCR (ddPCR) and culturing. Each method has its own limitations in terms of sensitivity, specificity, and the ability to distinguish between infectious and non-infectious particles.
- **Health and Safety Risks**: Handling and analyzing potentially infectious airborne viruses pose health and safety risks to researchers and require stringent biosafety protocols to prevent contamination and exposure.

The airborne microbes, their sources, spreading and viability in air, especially the ones capable of spreading between humans, remain poorly known. Also, the general knowledge related to airborne spreading of pathogens has been poor. For example, the characterization of short-range transmission i.e. airborne concentrations near the source, but when can the approximation of uniform indoor concentration be applied? This is mainly caused by the lack of suitable collection and measurement instruments that would enable either collection or realtime detection and identification of airborne pathogens.

3.1.2 Future research needs

For the health and safety of human society during upcoming epidemies caused by airborne pathogens, it is utmost important to improve the collaboration between aerosol scientists, microbiologists, medical doctors and many other disciplines in order to develop affordable, accurate, realtime instrumentation capable of fast detection of pathogens directly from air. Low price would enable widespread measurements and monitoring of pathogens, realtime instrumentation would enable realtime detection of unsafe environments in quickly changing situations.

Direct measurement from air would remove artefacts and time-resolution issues related to filter collections. In addition, more information is needed about spreading, spatio-temporal variation and behaviour and survival of airborne pathogens in different environments with different ventilation systems. Ideally, the solution would combine the latest scientific understanding on pathogen behaviour with accurate, real-time detection methods and atmospheric transport modelling of particulates or plumes, to offer predictability beyond the capabilities of one instrument or fixed location. This will most likely require years of active inter-disciplinary research and technological innovations.

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3.2 Saliva and anterior nasal sample for detecting respiratory viruses in children

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Abstract: Cost-effective, simple and reliable tests for viral infections are needed now and in the future. Our aim is to compare saliva and anterior nasal sampling with nasopharyngeal sampling for respiratory viruses in children in pediatric emergency department. Especially anterior nasal sample had good sensitivity and specificity for detecting respiratory viruses.

3.2.1 Introduction

The eruption of COVID-19 pandemic showed the importance of simple and fast diagnostic methods. Studies investigating the connection between virus etiology and clinical disease presentation are needed for the treatment and prevention actions to be aimed right. Unlike any previous epidemic, COVID-19 pandemic with global impact erupted the need for more efficient modern virus diagnostics. Respiratory viruses are known to replicate in the nasopharynx, and also of coronavirus 2 (SARS-CoV-2) the biggest quantities have been measured in samples from the nasopharynx (Tsang, 2021). Nasopharyngeal sample collection is time-consuming, requires professionals, and is uncomfortable for the patient. Thus, the gold standard in COVID-19 diagnostics has been polymerase chain reaction (PCR) assay for detecting SARS-CoV-2 RNA in nasopharyngeal samples(Tsang, 2021, Moreira 2021, Tsujimoto 2021). However, due to testing inconvenience there is a need for other testing methods. The advantage of both saliva sample and anterior nasal sample is the ease and reproducibility of sampling with no complications associated with sampling (Tsang, 2021).

The aims of the present study are: to compare the sensitivity and specificity of nasopharyngeal, anterior nasal and saliva tests in respiratory microbial diagnostics in children with acute respiratory infection and to analyze the role of respiratory pathogens in connection to patients´ symptoms.

3.2.2 Patients and methods

62 children aged 0-14 years were recruited in the emergency department, New Childrens Hospital, Helsinki between March and April 2023, and November 2023 and February 2024. Patients visited the emergency department due to symptoms of respiratory infection and were recruited during their visit if they were tested as a

part of normal clinical practice for respiratory infections with a nasopharyngeal fourplex PCR test for SARS-CoV-2, influenza A, influenza B and respiratory syncytial viruses. After an informed consent, anterior nasal sample and saliva sample were taken. Anterior nasal sample was taken with a cotton swab from the anterior nasal mucosa. Saliva sample was taken with a cotton swab from the mucosa of the mouth.

The patients or their guardians filled in structured forms about background information and the presence and timespan of the respiratory symptoms: fever, cough, breathing difficulties, sore throat, runny nose, headache, muscle pain, diarrhea, emesis/vomiting, rash. An open question about the symptoms and enquiries of the general condition were also included. The guardians and patients 4 years old and above were asked to evaluate the tolerance of different types of testing on a scale from 1 (pleasant) to 5 (unpleasant). Nurse taking the samples evaluated the ease of sampling on a same scale with 5 steps. Children with significant comorbidities which could effect the sample collection evaluation were excluded from the study.

The nasopharyngeal swabs were analyzed with Xpert® Xpress CoV-2/Flu/RSV plus test (Cepheid). Later these as well as anterior nasal and saliva samples were analyzed with Biofire Filmarray Respiratory Panel 2.1 plus test (BioMerieux). This is a cartridge-based multiplex PCR test that detects adenoviruses, coronaviruses SARS-CoV-2, NL63, HKU1, 229E, OC43 and MERS-CoV, rhino/enteroviruses, influenza A virus, influenza B virus, parainfluenza 1-4 viruses, respiratory syncytial virus, human metapneumoviruses, *Bordetella pertussis, Bordetella parapertussis, Chlamydia pneumoniae,* and *Mycoplasma pneumoniae*.

The Helsinki and Uusimaa Hospital District Ethics Committee approved the study protocol, and institutional research approval was granted by Helsinki University Hospital, Helsinki, Finland. Written informed consent was obtained from all caregivers. Participating in the study was voluntary and did not affect the treatment of the patient. Anterior nasal testing caused transient minor inconvenience and very small risk for nasal bleeding. Salivary testing does not produce pain and the amount of saliva needed for the sample is small.

The nonparametric Mann-Whitney correlation test was used to investigate the associations between the variables. The groups were compared using Mann-Whitney U-test as appropriate. Statistical analyses were performed using SPSS software version XX (SPSS Inc., Chicago, IL). Differences were considered significant when the P-value was <0.005.

3.2.3 Results

This study material included altogether 19 SARS-CoV-2 positive and 21 rhino/enterovirus positive nasopharyngeal swabs by Biofire Respiratory panel. Of anterior nasal swabs, 18/19 SARS-CoV-2 positives and 17/21 rhino/enterovirus positives were positive. Saliva was SARS-CoV-2 positive for 14/19 patients and rhino/enterovirus positive for 12/21 patients. 8/9 RSV positive patients were

positive for anterior nasal and saliva, too. The numbers of positive samples were low for other pathogens.

Table 1. Detected pathogens from different sample types with Biofire Respiratory panel. Pathogens that were not detected in any sample, are omitted.

	nasopharynx		anterior nasal		saliva	
	positive	**negative**	**positive**	**negative**	**positive**	**negative**
rhino/entero	21	38	17	42	12	47
SARS-CoV-2	19	40	18	41	14	45
RSV	9	50	8	51	8	51
Inf A	3	56	3	56	3	56
hMPV	2	57	2	57	2	57
ADV	2	57	3	56	2	57
M. pneumoniae	2	57	1	58	2	57
PIV1	1	58	0	59	0	59
PIV2	1	58	1	58	0	59
NL63	1	58	1	58	0	59

All children recruited in the study had respiratory symptoms. The main reason to enter the emergency department was high or prolonged fever in 25 (45 %) and difficulty in breathing in 18 (32 %) patients. Fever (over 38 °C) and cough were the most frequent symptoms both in 42 (75 %) patients, followed breathing difficulty 31 (55 %), sore throat 10 (18 %), runny nose 29 (52 %), diarrhea 5 (8.9 %) and nausea/vomiting 9 (16 %) patients. Four patients reported headache (7.1 %), three muscle pain (5.4 %), two rash (3.6 %) and one patient disorientation (1.8 %). 28 (50 %) patients were treated in the hospital ward, one at the intensive care unit. The length of hospital stay varied between 1 and 5 days, median 2. Three patients were diagnosed with pneumonia, 4 otitis media, 3 pyelonephritis, 1 peritonsillar abscess. Cough ($p=0.049$) was the only symptom connected to positive RSV. Fever ($p=0.027$), breathing difficulty ($p=0.0498$) and runny nose ($p=0.035$) were connected to positive RSV as the duration of these symptoms increased the probability of positive RSV test. As influenza A was found in only three patients the correlation to certain symptoms is not statistically significant. For SARS-CoV-2 fever ($p=0.047$) was the only symptom with association to positive test. Runny nose was connected to positive SARS-CoV-2 but did not reach statistical significance ($p=0.054$). Patients who did not need hospital care had more SARS-CoV-2 than those who needed hospital care ($p=0.004$).

3.2.4 Conclusions

Saliva sample and anterior nasal sample gives promising results as a more comfortable, easy and less staff demanding yet accurate sample type for detecting viral infections in children with respiratory symptoms in the emergency ward by multiplex PCR. Saliva and anterior nasal sample are preferred against nasopharyngeal samples among patients and caregivers due to less discomfort and anxiety. Especially anterior nasal sample had good sensitivity and specificity for detecting respiratory viruses. Larger studies with larger populations are needed to assure a new gold standard. Based on our present study the etiology of respiratory symptoms in symptomatic children is not determinable by clinical presentation.

3.2.5 Acknowledgements

We want to thank every little patient and their families. A big thank you also goes to the staff of HUS New Children's Hospital and HUSLAB.

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3.3 Saliva samples in SARS Cov-2 virus detection compared to the nasopharyngeal RT-PCR findings in individuals with suspected COVID-19 infection

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Abstract: The gold standard in COVID-19 diagnostics is time consuming and inconvenient RT-PCR assay for detecting coronavirus RNA in nasopharyngeal swabs. Tests of using saliva samples instead of nasopharyngeal swabs give conflicting results. The objective is to compare saliva samples tested by different laboratory methods to nasopharyngeal analysis in SARS-CoV-2 suspected individuals. The results show that saliva samples are easy and comfort to collect and the results are comparable to those of the nasopharyngeal samples.

3.3.1 Introduction

The current gold standard in COVID-19 diagnostics is real-time reverse transcription polymerase chain reaction (RT-PCR) assay for detecting coronavirus 2 (SARS-CoV-2) RNA in nasopharyngeal swab (NPS) samples (Tsang, 2021, Mannonen, 2021, Corman, 2021). NPS testing requires staff, is expensive, time consuming, inconvenient for the subjects it has a higher chance of staff exposure as well. The advantage of the saliva sample is the ease and reproducibility of sampling, no complications associated with sampling, (Tsang, 2021). In the existing literature the relevance of using saliva samples gives conflicting results. Our objective was to compare saliva samples to NPS samples in SARS-CoV-2 suspected individuals.

3.3.2 Materials and methods

A total of 153 single time point from each adult patients (from February 8th to March 3rd 2022) who have been referred to the HUSLAB Meilahti Corona Testing Point due to COVID-19 suspicion, have given their voluntary consent to biobank sampling for non-stimulated saliva sample**.** Saliva samples were stored frozen, and then thawed immediately before diluted and lysed for nucleic acid extraction and RT-PCR

Two SARS-CoV-2 RT-PCR tests on saliva (1) the cobas® SARS-CoV-2 RT-PCR test, and 2) the quantitative and qualitative Roche RT-PCR tests (Roche)), are compared with nasopharyngeal swabs taken in 1.5 ml 0.9% NaCl, analyzed either with one of the two commercial tests, cobas® SARS-CoV-2 (Roche) and Amplidiag COVID-19 (Mobidiag/Hologic) or a laboratory-developed test (2,3) (HUS

Diagnostic Center, HUSLAB). Of note, saliva is so far only approved for Roche's classic qualitative test.

The study is the Biobank Study and patients will not be contacted. The study uses Biobank samples to which the patient has given their consent.

All research results are published in a fully anonymized form and used and stored according to official regulation (HUS Secure operating environment, HUS Acamedic).

3.3.3 Results

SARS-CoV-2 test (Qualitative) for Cobas 6800 (Roche): Sensitivity of saliva test compared to nasopharyngeal swab was 97% and specificity of saliva compared to nasopharyngeal swab was 96%.

Table 1. Saliva test compared to nasopharyngeal swab

	Roche SARS-CoV-2 saliva	
Roche SARS-CoV-2 nasoph swab	Positive	Negative
Positive	60	2
Negative	3	80

Saliva samples, SARS-CoV-2 test Duo (Quantitative) (Roche) for Cobas 6800 Sensitivity of Duo test compared to qualitative assay was 98% and specificity of Duo test compared to qualitative assay was 98%.

Table 2. Sensitivity of Roche SARS-Cov-2 Duo test compared to qualitative assay

	Roche SARS-CoV-2 Duo saliva	
Roche SARS-CoV-2 saliva	**Positive**	**Negative**
Positive	49	1
Negative	1	60

3.3.4 Conclusions

The corona pandemic and viral mitigation has clearly demonstrated the importance of modern virus diagnostics. In the present study saliva samples are easy and comfort to collect and the results are comparable to those of the nasopharyngeal samples.

3.3.5 Acknowledgements

We thank Laboratory technician Elina Mondolin (HUS Diagnostic Center) and Laboratory technician students Anne Ahonen and Niko Heinonen (Metropolia Univeristy of Applied Sciences).

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3.4 Detecting Viral Infections via Headspace Volatile Organic Compound Analysis

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EXTENDED ABSTRACT

3.4.1 Background

Many common respiratory viruses have been shown to spread through the air. Infective aerosols that are generated during respiratory activities transmit effectively indoors and can expose larger group of people compared to the droplet or fomite transmission of pathogens. This poses significant challenges in controlling epidemics, particularly during asymptomatic transmission (Wang et al., 2021, You 2024). Thus, there is a clear demand for rapid and accurate diagnostic methods and screening.

The current gold standard for diagnostics is PCR testing, which is both time-consuming and invasive. So, there is a growing need for non-invasive, real-time diagnostics to help control the spread of infections in public spaces (Wintjens 2021). Previous research has demonstrated that VOCs can reflect the metabolic and pathophysiological processes of infected cells, making them a promising avenue for non-invasive diagnostics (Traxler et al., 2018). This study examines VOC profiles of cells infected with Influenza A H1N1 and seasonal coronaviruses OC43 and NL63, aiming to identify VOC "fingerprints" that can differentiate between infections. The ability to rapidly and non-invasively detect respiratory infections could significantly contribute to public health efforts by enabling real-time environmental screening and individualized diagnostics.

3.4.2 Methods

This experimental study used in vitro cell cultures infected with Influenza A H1N1 and seasonal coronaviruses OC43 and NL63. VOC emissions from infected cells were analyzed using two techniques: proton-transfer-reaction time-of-flight mass spectrometry (PTR-TOF) and differential mobility spectrometry (DMS). VOC measurements were taken every 12 hours for seven days. Non-infected cell cultures served as controls to ensure the VOCs detected were virus-related.

3.4.3 Results

VOCs produced by infected cells showed distinct patterns based on the virus type. Four VOCs peaked during Influenza A H1N1 and OC43 infections, while no significant changes were observed in NL63-infected cells. VOC concentrations began increasing within 48 hours of infection, indicating that VOC analysis could serve also as a method for early-stage detection. These findings suggest that each virus produces a unique VOC signature, which could be used to distinguish between different respiratory infections. The most prominent VOC identified was acetaldehyde, which has been also previously associated with viral infections (Traxler et al., 2018).

3.4.4 Discussion and conclusions

The results demonstrate that VOC analysis has the potential to differentiate between respiratory viruses, offering a non-invasive and real-time diagnostic tool. This technology could be applied in both individualized diagnostics and public health monitoring in high-risk areas, such as hospitals or crowded public spaces. The findings are consistent with previous research on VOCs from viral infections, and further studies should validate these results in clinical settings.

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3.5 Effect of vocalization on human aerosol dynamics

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EXTENDED ABSTRACT

3.5.1 Background

Respiratory particles are thought to be generated throughout the respiratory tract during breathing and other respiratory and phonatory activities including e.g., coughing, speaking and whispering. There are two main mechanisms underlying particle generation. Firstly, fluid film, filament, or bubble breakage or bursting (FFBB) and secondly, turbulent aerosolization. In FFBB fluids, filaments or bubbles are formed by various mechanisms and breaking of these thin film structures results in small airborne particles. In turbulent aerosolization the turbulent airflow causes shear-induced surface wave instability and as a result small particles are stripped from a fluid film. In this work, we aimed to study the effect of vocalization on particle production in trained singers to better understand the role of the larynx and upper respiratory tract in the generation of particles.

3.5.2 Methods

The methods are described in detail a dedicated abstract in this report. Briefly, the measurements were conducted in a custom-made measurement chamber providing controlled and particle-free environment for the tests. Emitted particles were measured using a condensation particle counter (CPC 3775, TSI Inc., Shoreview, MN, USA, range ca. 0.004 µm to 3 µm) and aerodynamic particle sizer (APS 3321, TSI Inc., Shoreview, MN, USA, range ca. 0.5 µm to 10 µm). The size distributions are measured and reported in dry state. The APS data were divided into > 1 µm and < 1 µm particle size fractions for statistical analysis. 44 subjects

were recruited to the study through announcements distributed among professional singers, representatives of choirs and singing teachers in Finland.

Generalized linear mixed model was constructed to model particle generation using gamma distribution with logarithmic link function. Subject ID was used to account for random effects and wald method was used to compute the confidence intervals. Akaike information criteria (AIC) were used to guide the model selection.

3.5.3 Results

In the statistical modelling no easily measured variable, such as age, sex, BMI or pulmonary function, was able to predict the aerosol emission with any accuracy. However, different vocalizations had marked marked effect independently from associated exhaled flow rate or sound pressure level. For example, sound pressure normalized whispering produced over two fold more particles than speaking. The phonetic structure of the speech was also a statistically significant factor affecting aerosol emission.

3.5.4 Discussion and conclusions

We observed significant differences in particle production between different vocalizations which were not explained by sound pressure level of the generated utterances. For example, whispering produced more particles of all sizes compared to speaking the same sentences in a normal voice. This indicates that in addition to sound pressure, flow rate, and vibration of the vocal folds, other factors related to the physiology of the larynx also affect the amount of particles produced by humans.

3.6 Verification of the viral qPCR methods

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Abstract: During the last years, interest in measurement of viruses in the breathing zone has increased. The aim of this work was to optimize quantitative PCR methods of several types of viruses that can be analyzed from settled dust samples. Finally, five different viral assays were optimized and verified for the quantitative use for samples collected from indoors. Selected viruses were SARS-CoV-2, Influenzas A and B, and Norovirus genotype GI and GII.

3.6.1 Introduction

Reliable measurements of different microbes have been successfully performed from settled dust samples collected from indoor environments, primarily detecting molds, yeasts and bacteria. This allows for the quantification of microbes present in the breathing zone and thereby assessing exposure to these microbes.

With the onset of the COVID-19 pandemic, interest in quantitatively measuring viruses in the breathing zone has increased. The aim of this project task was to optimize and verify quantitative PCR methods for several types of viruses that can be analyzed from settled dust samples. The method development covers the entire process from sample collection, sample preprocessing, and isolation methods to the verification of PCR methods.

3.6.2 Methods and results

Sampling and sample preparation

Different methods for collecting settled dust samples have been tested previously, and the most effective method involves collecting settled dust on a standard-sized petri dish for a known time period (Adams et al. 2015). Sampling locations and height of the sampling was known, and sampling was done not close to ventilation or other major air flows.

At the end of sampling, the dish was sealed with parafilm and sent by mail to the laboratory by mail, where the samples were processed within a week. Samples were stored at room temperature if necessary, but in practice, they were usually processed the day after arrival. The sample was pretreated by moistening a cotton swab (FloqSwab, Copan) with DNA/RNA shield solution (Zymo Research), thoroughly wiping dust from the inside of the lid and the base of the petri dish and storing the swab in an Eppendorf tube at -80°C before RNA extraction.

RNA Extraction

Before starting RNA extractions, the extraction of cotton swabs into the lysis buffer of the RNA extraction kit and Zymo's DNA/RNA Shield were tested. Both buffers should work well for lysis. Based on our test results, the lysis buffer of the extraction kit was chosen.

The optimal method for RNA pretreatment was as follows: 600 µl of the kit's lysis buffer is pipetted into a deep-well plate, and each cotton swab is inserted into its well with sterile tweezers. This 96-well plate is vortexed for 2 minutes (using a vortex with a 96-well plate adapter). Afterward, the obtained liquid is transferred to a new 96-well plate for further extraction. Once the extraction is complete, the RNA is transferred from the device's elution plate to a low-profile 96-well Eppendorf plate using a pipetting robot, from which it is pipetted for cDNA synthesis. The remaining RNA is frozen on this plate at -80°C.

For RNA extraction, the Chemagic Viral300 DNA/RNA Kit performed with the Chemagic 360 robot, was used. The different RNA extraction methods for viruses that were previously tested were: the Chemagic Viral300 DNA/RNA Kit (Perkin Elmer) with the Chemagic 360 robot; the Mag-Bind® Viral DNA/RNA 96 Kit (Omega Biotek) with the Kingfisher Flex robot; and the HP Viral RNA Kit (Roche) performed manually. At that time, the best method was found to be the extraction performed with the Chemagic 360 robot (Chemagic Viral300 DNA/RNA Kit).

Also, the inclusion of the internal standard, the so-called ‘salmon’. (Deoxyribonucleic Acid Sodium Salt from Salmon Testes; Sigma-Aldrich), was tested. This is used in other qPCR analyses in the laboratory. Salmon did not interfere with the extraction, and the salmon results were normal when analyzed for concentration with the salmon qPCR assay (Haugland et al. 2005). It was decided to add 10 µl of salmon to the samples to monitor the success of the extraction for each sample.

cDNA Synthesis

Two different synthesis kits were tested for cDNA synthesis: Maxima H cDNA Kit (Thermo Fisher Scientific) and Superscript IV Vilo Mastermix (Invitrogen), with the latter, known as the Vilo Mastermix, being selected as the final choice. We tested synthesizing several different amounts of RNA: 1 µl, 2 µl, and 5 µl. In the end, there was such a small difference in the qPCR Ct values between 2 µl and 5 µl that 2 µl was chosen.

Since we need a large amount of cDNA for various qPCR applications, we also tested 1x, 2x, and 3x reactions in the same well. Due to reagent consumption, we selected a 2x reaction, meaning the same sample is pipetted for cDNA synthesis in double the amount into one well.

qPCR

There was particular interest in respiratory viruses and those that could be studied from settled dust. We focused the method development to influenza viruses (A and B) and coronavirus (SARS-CoV-2). Eventually, a quantitative RT-PCR method was also optimized for Norovirus genogroups GI and GII, performed as a so-called one-step application, where reverse transcription is done in the same run with the qPCR analysis. For other applications, a separate cDNA synthesis was performed with Vilo mastermix since cDNA is more stable than RNA.

All methods were optimized for the QuantStudio6 Pro (Applied Biosystems) device.

N1 assay for SARS-CoV-2 virus

Several different PCR assays were tested to detect SARS-CoV-2 virus, and N1 assay (detecting N gene from SARS-CoV-2 virus) published by Lu et al. (2020) was selected. Annealing temperature and primer & probe concentrations were tested carefully, and the best combination was selected (Table 1). For enzyme testing three different commercial enzyme mixes were tested; Universal Mastermix (Applied Biosystems), Environmental Mastermix (Applied Biosystems) and TaqPath™ BactoPure™ Microbial Detection Master Mix (Applied Biosystems). Environmental Mastermix was selected because of the good efficiency and sensitivity.

Standard curve was done using a quantitative control from European commission Joint research centre; ssRNA-control EURM-019. Copy number for the N1 gene was 7,3x10e7 cp/µl.

Table 1. Information on the composition of the N1 assay

SARS-CoV-2 N1 assay	1x (µl)	Sequences for primers and probes
Environmental master mix	12,5 µl	
N1 F- primer (10µM)	1,25 µl	GACCCCAAAATCAGCGAAAT
N1 R- primer (10µM)	1,25 µl	TCTGGTTACTGCCAGTTGAATCTG
N1 probe (10µM)	0,31 µl	FAM-ACCCCGCATTACGTTTGGTGGACC-BHQ1
Nuclease free H_2O	7,69 µl	
template cDNA	2 µl	
total	25 µl	

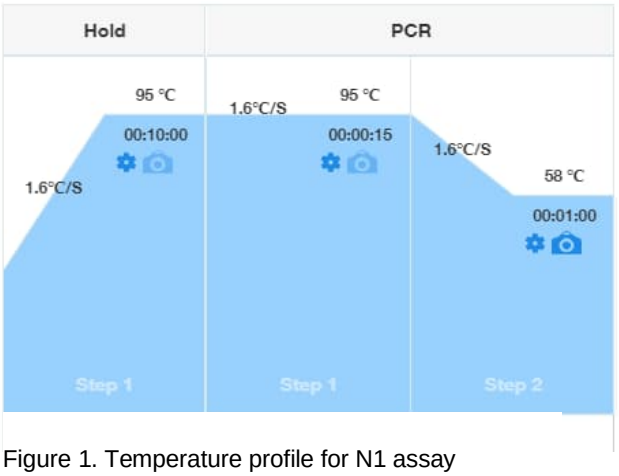

Figure 1. Temperature profile for N1 assay

Influenza A and B

For Influenza A and B detection two different primer & probe sets were tested for both viruses. Selected primers and probes are presented in tables 2 and 3 and those are published in US Centers for Disease Control and Prevention (CDC) website.

Primer and probe concentrations were tested as follows (F+R+P); 800+800+200 nM, 400+400+200 nM, 900+900+300 nM, 800+800+400 nM.

For the Inf-A assay best combination was 400+400+200 nM, and for the Inf-B assay 800+800+200 nM.

Following annealing temperatures were tested: 56, 58, 60 °C. Finally, 60 °C was selected for both, Inf-A and Inf-B assays.

Table 2. Information on the composition of the Influenza A assay

Inf-A assay	**1x (µl)**	**Sequences for primers and probes**
Environmental master mix	12,5 µl	
InfAFor1 (10µM)	1 µl	CAA GAC CAA TCY TGT CAC CTC TGA C
InfARev1 (10µM)	1 µl	GCA TTY TGG ACA AAV CGT CTA CG
InfA-P1 (10µM)	0,5 µl	FAM- TGC AGT CCT CGC TCA CTG GGC ACG - BHQ1
Nuclease free H_2O	8 µl	
template cDNA	2 µl	
total	25 µl	

Table 3. Information on the composition of the Influenza B assay

Inf-B assay	**1x (µl)**	**Sequences for primers and probes**
Environmental master mix	12,5 µl	
InfBFor1 (10µM)	2 µl	TCC TCA AYT CAC TCT TCG AGC G
InfBRev1 (10µM)	2 µl	CGG TGC TCT TGA CCA AAT TGG
InfB-P1 (10µM)	0,5 µl	FAM- CCA ATT CGA GCA GCT GAA ACT GCG GTG - BHQ1
Nuclease free H_2O	6 µl	
template cDNA	2 µl	
total	25 µl	

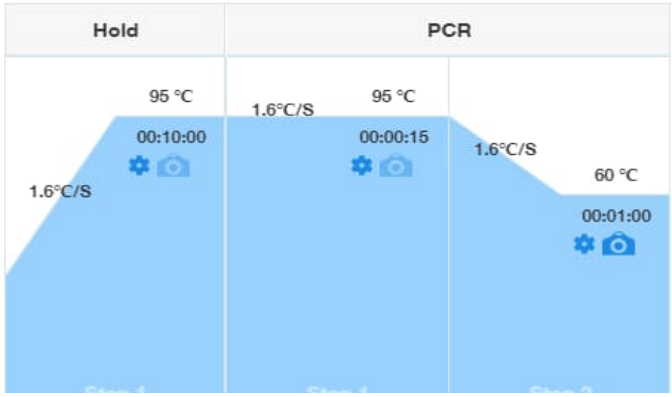

Figure 2. Temperature profile for Inf-A and Inf-B assays

Standard curves were done from commercial RNA controls with known concentration. Amplirun influenza A H1 RNA control (Vircell) for Inf-A assay and Amplirun influenza B RNA control (Vircell) for Inf-B assay.

Norovirus

Two different applications were optimized for Norovirus: one for genogroup GI and another for genogroup GII.

For both groups, two different primer-probe combinations were tested. The first combination had issues with amplification efficiency, and the applications could not be optimized to be sufficiently reliable. Optimization of the second set of applications was also challenging, and it was decided to develop the Noro GI and GII applications as so-called one-step applications. In these, the analysis is performed directly from RNA, and reverse transcriptase (RT) is included at the beginning of the qPCR run. Therefore, no separate cDNA synthesis is done before the qPCR run.

The best methods were determined to be based on the primers published by Kauppinen et al. (2014) (Table 4 & 5).

Primer and probe concentrations were tested as follows (F+R+P);

400+400+200 nM, 600+600+200 nM, 600+600+400 nM, 800+800+400 nM and for both, GI and GII combination of 800+800+400 nM was chosen.

Following annealing temperatures were tested: 56, 58, 60 and 62 °C. Finally, 60 °C was selected for both assays.

Two RNA template amounts, 2µl and 5µl, were tested, and we found that both assays need 5 µl template RNA to work properly.

Table 4. Information on the composition of the Norovirus GI assay

Norovirus GI	**1x (µl)**	**Sequences for primers and probes**
TaqMan™ Fast Virus 1-Step Master Mix	6,25	
NVGIF (10µM)	2	GCYATGTTCCGCTGGATG
NVGIR (10µM)	2	CCTTAGACGCCATCATCATT
NVGIP-MGB (10µM)	1	VIC-TGGACAGGAGAYCGC-MGB-NFQ
Nuclease free H_2O	8,75	
template RNA	5	
total	25	

Table 5. Information on the composition of the Norovirus GII assay

Norovirus GII	**1x (µl)**	**Sequences for primers and probes**
TaqMan™ Fast Virus 1-Step Master Mix	6,25	
QNIF2d (10µM)	2	ATGTTCAGRTGGATGAGRTTCTCWGA
COG2R (10µM)	2	TCGACGCCATCTTCATTCACA
P1 (10µM)	1	FAM-TGGGAGGGCGATCGCAATCT-BHQ1
Nuclease free H_2O	8,75	
template RNA	5	
total	25	

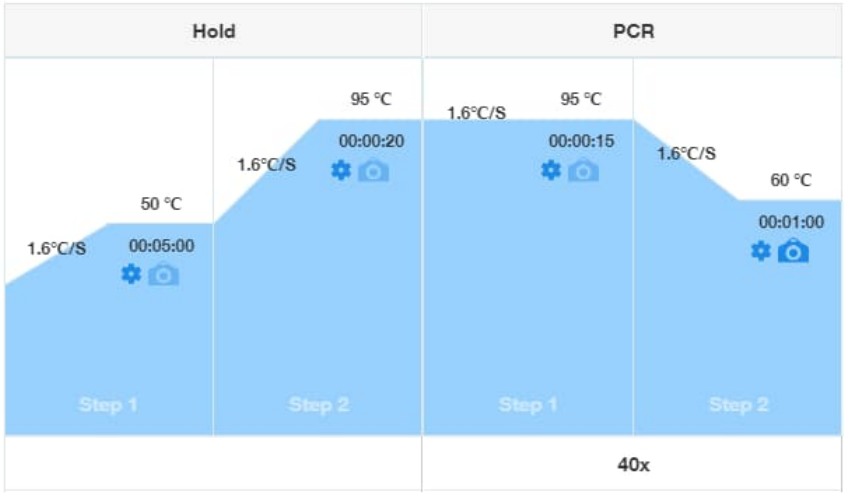

Figure 3. Temperature profile for Norovirus GI and GII assays

The standard curve was analyzed using a G-blocks standard (IDT) synthesized for the target sequence. The standard curves for both methods meet the general quality requirements used by the team regarding linearity (a slope close to 3.32 and an R^2 above 0.98) and efficiency (Eff% 90-110). However, both the slope and efficiency are suboptimal for the GI application.

3.6.3 Quality assurance

Each qPCR run includes various positive and negative controls at two dilution points for each assay. For instance, every Inf-A run also includes controls for Inf-B and N1, which are required to test negative (i.el false-positive detetion). Additionally, no-template controls (NTC) are in every qPCR run. A process-positive sample, which is a SARS-CoV-2 positive sample that has been treated to be non-infectious, goes through the RNA extraction, cDNA synthesis and qPCR run. Similarly, deactivated controls that go through the entire process were used for Noroviruses.

3.6.4 Summary

All the mentioned applications have been tested, optimized, and verified for use in the laboratory of the THL Indoor Environment -team. The methods have been optimized and tested to the extent that their reliability can be trusted when studying the target virus from samples collected in indoor environments. Quality assurance procedures and usage guidelines have been created for the laboratory.

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3.7 A method for human individual respiratory particle measurement

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EXTENDED ABSTRACT

3.7.1 Background

The COVID-19 pandemic and seasonal respiratory epidemics have deepened our understanding of infection risk. Respiratory infections primarily spread through airborne particles emitted by infected individuals. Emission patterns (aerosols and droplets) vary widely among individuals during activities like breathing, speaking, singing, and coughing (Alsved et al., 2020; Morawska et al., 2009). Assessing airborne pathogen risk involves considering particle emission rates, size distributions, dispersion, dilution, and pathogen lifetime. There are several challenges associated with measuring respiratory particles. The particle size range is wide, and they are released in very small concentrations that vary temporally and spatially. In addition, dilution, evaporation and losses of the particles during sampling should be considered.

Here we present a method and preliminary results for the measurement of respiratory aerosol particulate emissions. The instrumentation was used to study the respiratory aerosol emissions of test subjects under laboratory conditions but can also be used for field studies.

3.7.2 Methods

This paper introduces a novel portable measurement system for studying respiratory particle emissions. The system features an aerosol chamber with a volume of approximately 0.5 m^3. After passing clean compressed air through a HEPA filter, the background aerosol concentration is effectively reduced to zero. Participants place their faces inside the chamber for emission measurements. The chamber maintains a temperature of around 20°C, with relative humidity below 1%. This low humidity ensures rapid drying of respiratory droplets. The portable measurement system is shown in Figure 1.

Aerosol emissions are collected using an aerosol sampling funnel positioned approximately 5 cm from the subject. The sampling flow rate is 40.5 LPM. Several aerosol instruments (including TSI APS 3321, Palas Fidas Frog, TSI CPC 3775

TSI, and Airmodus CPC A23) measure emissions across a wide particle size range (0.004–10 µm). Particle losses within the sampling line are characterized using the APS instrument.

Additionally, CO_2 emissions are monitored using a high-speed instrument (LI-840A, LI-COR Inc) to analyze aerosol dilution. Sound pressure levels produced by the subject are recorded from a distance of approximately 10 cm.

Based on the dilution ratio and absolute concentration measured with the CO_2 device, the relative humidity of the sampling line typically falls between 40% and 55%. Given a sampling time exceeding 2 seconds, respiratory droplets are estimated to dry before measurement.

Figure 1. The portable measurement system for respiratory aerosol emission studies.

3.7.3 Results

The measurement set-up allowed for the determination of particulate emission coefficients from the respiratory tract. Testing of a single subject resulted in median particle number and mass emission coefficient values ranging from 80-60 000 1/s and 0.4-200 ng/s, respectively.

The size distribution of dry respiratory aerosols was measured over the size range 0.004 - 10 µm with a time resolution of 1 second. Particle number is dominated by particles smaller than 0.023 nm. The particle size measured by Palas Optical Particle Counter (OPC) was about 2.5 times smaller than that measured by APS. Due to the significant difference in particle sizes, there was also a significant difference in mass concentrations. As the APS provides more accurate aerodynamic diameter data, we prefer the APS over the OPC in respiratory particle measurements.

The CO2 measurement allowed the calculation of the dilution factor and the exhalation flow rate of the aerosol sample. Our results show that even the maximum exhaled flow rate in coughing was less than the total airflow rate (40.5 LPM). Therefore, we estimate that all particles were captured in the sample flow. Sample dilution is a balancing act between sufficiently drying the particles and over-diluting them, leaving too few particles to measure. Particle losses in sampling line increased rapidly for particles larger than 6 µm (dry size), indicating an increase in particle inertial losses.

3.7.4 Discussion and conclusions

The study revealed the following key findings regarding respiratory aerosol particles. Most aerosol particles measured were smaller than 0.5 µm. However, most of the particle mass resided in larger particles exceeding 1 µm. These results align with previous observations, where the highest concentration of respiratory particles was estimated around 0.1 µm in size (Pöhlker et al., 2023). Emission levels varied significantly across activities (breathing, speaking, singing, and coughing). A critical question arises: Are particle emissions by mass concentration more critical than by number concentration? Larger particles may carry more infectious pathogens, warranting further investigation.

Notably, particle emissions correlated strongly with sound pressure. Interestingly, particle emissions also correlated with CO_2 concentration. Monitoring CO_2 levels can serve as a useful indicator for assessing airborne aerosol emissions and dilution indoors.

In summary, understanding the dynamics of respiratory particle emissions is vital to understanding the risk of infection and implementing effective preventive measures. Future research should continue to address these challenges and improve our understanding of the dynamics of airborne infection.

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3.8 Elemental analysis of single ambient aerosol particles using laser-induced breakdown spectroscopy

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EXTENDED ABSTRACT

3.8.1 Background

Aerosol particles affect human life in numerous ways, including cloud dynamics, premature mortality, disease transmission, and visibility impairment. Studying these effects is particularly challenging when particle concentrations are very low, as in ice nucleation in the atmosphere and the airborne transmission of diseases like COVID-19. Ice-nucleating particles (INPs) and respiratory emissions are often present in such low concentrations that their composition must be analysed on a single particle level.

Traditional methods of aerosol particle analysis involve collection followed by laboratory examination, but these methods suffer from reduced temporal resolution and potential artefacts. Real-time aerosol mass spectrometry provides detailed information with rapid sampling rates but is costly and complex. Laser-induced breakdown spectroscopy (LIBS) offers a simpler, cost-effective alternative without the need for vacuum conditions, though it requires high particle concentrations or focusing techniques.

We introduce a novel method for focusing particles for LIBS analysis using size amplification aided aerosol charging and linear electrodynamic quadrupole focusing. This method enables real-time elemental analysis of single aerosol particles from ambient air without concentration limits, using low laser pulse energies. Our approach is especially beneficial for studying low-concentration phenomena, such as aerosol emissions from the human respiratory tract.

3.8.2 Methods

In the developed method, aerosol particles are first grown with water supersaturation, charged with a corona charger, and then focused with a linear electrodynamic quadrupole. As the particles are focused into a well-defined focus line, laser-induced breakdown spectroscopy is utilized to analyse their elemental composition.

3.8.3 Results

In the proof-of-concept series ambiently sampled aerosol particles could be precisely controlled with the linear electrodynamic quadrupole, which enabled their LIBS analysis. Particles could be analysed down to a couple of hundred nanometres with a sampling rate of a few particles/minute. Spectra of aluminium, calcium and sodium were presented in the paper, analysed from ambient aerosol particles. The ability to utilize LIBS in ambient aerosol analysis in such repeatable manner is unprecedented in aerosol technology. The technology has vast potential to become a portable analysis platform for various applications in the field of aerosol analysis.

3.8.4 References

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4 Air transmission of pathogens

4.1 Computational fluid dynamics (CFD) in pandemic prevention

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Abstract: This study investigates computational fluid dynamics (CFD) methodologies for simulating indoor air flows and particles emitted by humans, including potential pathogens, through activities like speaking, coughing, and sneezing. It discusses the use of Reynolds-Averaged Navier-Stokes (RANS), Detached Eddy Simulation (DES), and Large Eddy Simulation (LES) models, and compares the passive scalar approach with the Lagrangian method for particle dispersion. The study underscores the importance of advanced turbulence models and high-performance computing (HPC) for accurate predictions in indoor environments. The article further details how CFD can be employed to assess infection risk, enabling the design of facilities that are safe during pandemics.

4.1.1 Introduction

Computational fluid dynamics (CFD) is a branch of science dedicated to utilising computers to solve complex equations that describe the behaviour of fluids (both gas and liquid) and the particles within them under various conditions. This typically necessitates high-performance computing (HPC), which involves using computers with far greater capabilities than standard ones.

Prior to the emergence of COVID-19, extensive research had already been undertaken to comprehend indoor airflows and the dispersion of pathogens emitted by humans. However, the arrival of COVID-19 multiplied research efforts in this area significantly. One notable study on simulation techniques, conducted early in the pandemic, was published by Vuorinen et al., (2020). Since then, numerous articles have been published on the subject.

4.1.2 Turbulence in indoor air

Modelling turbulence in indoor air flows and in different ventilation strategies is exceptionally challenging due to the intricate and dynamic nature of the environment. Indoor airflows are influenced by numerous factors such as furniture arrangement, heat sources, and human activities, all of which introduce a variety of scales of motion and thermal gradients. The presence of obstacles and boundaries causes complex interactions between different air streams, leading to highly variable velocity and pressure fields. Moreover, indoor environments often involve low-speed, buoyancy-driven flows where turbulence is not fully developed, making standard turbulence models less suitable.

Activities like speaking, coughing, and sneezing generate unstable jets and particle spread, necessitating detailed transient simulations for precise capture. These phenomena require advanced turbulence models beyond Reynolds-Averaged Navier-Stokes (RANS), such as Detached Eddy Simulation (DES) and Large Eddy Simulation (LES), to effectively capture various scales of turbulent motion and deliver accurate predictions. Additionally, the need for high-resolution meshing places significant demands on computational resources, reinforcing the complexity of simulating turbulence in indoor air flows.

Despite these challenges, indoor flows are quite often calculated using standard RANS models such as k-ε or SST k-ω model, although these modelling methods are known to work suboptimal in this case. Recently, the situation has been simulated using methods far better tailored to it, including DES and LES (Auvinen et al., 2022).

In this work, both the RANS models, due to their relatively small computing resource requirements, which allows simulation of several situations, and more accurate and more demanding DES and LES models are utilized.

4.1.3 Human emitted particles in indoor air

The simulation of human-emitted particles such as those produced during speaking, sneezing, or coughing in computational fluid dynamics (CFD) incorporates methods that capture the complex nature of these phenomena. Two prominent approaches are the passive scalar approach and the Lagrangian method.

In the passive scalar approach, the emitted particles are treated as a scalar quantity that is advected by the flow field. This method simplifies the simulation by focusing on the dispersion of the particles without explicitly resolving their individual trajectories. It is particularly useful for modelling the spread of contaminants or aerosols in a room, allowing researchers to understand concentration distributions over time. However, this approach does not account for the discrete nature of the particles, which can limit its accuracy in predicting particle behaviours such as settling and evaporation, especially for the larger particles.

Conversely, the Lagrangian method simulates particles as discrete entities that move and interact with the fluid flow. This method is more computationally intensive but provides a detailed representation of particle dynamics. In this approach, particles containing both solid and liquid components are tracked individually. The liquid component evaporates rapidly upon release, altering the particle size and affecting its trajectory. This factor is vital for effectively modelling larger-scale human-emitted particles, particularly when considering droplet transmission, as it affects the distance and spread of these particles within indoor settings. By incorporating evaporation models and accounting for the solid core of the particles, the Lagrangian method offers a more realistic and comprehensive understanding of particle dispersion, deposition, and interaction with air flow. For instance, Nie et al. (2022) employ the Lagrangian method.

However, for airborne transmission, small particles can be effectively simulated using a passive scalar. Although both the passive scalar and Lagrangian methods were applied in this project, the findings presented in this report primarily use the passive scalar approach.

4.1.4 Using CFD results as a tool for infection risk assessment

Using CFD as a tool for infection risk assessment involves simulating the concentration of human-emitted particles in various locations within a room, thus allowing for the estimation of the amount of particles a healthy person inhale. By incorporating detailed simulations that model the dispersion patterns of aerosols researchers can map out high-risk zones within indoor environments.

Furthermore, with this data and various other parameters like infectious dose, it becomes possible to determine the likelihood of healthy individuals getting sick. At the time of writing, these parameters are, unfortunately, not known exactly, but as information of them increases, this new information can be incorporated in the simulations and thus more accurate predictions can be obtained.

4.1.5 Using CFD as a tool for more pandemic safe spaces

By analysing the resulting concentration fields, it is possible to estimate the exposure levels for individuals in different locations. This data is instrumental in designing ventilation and purifying strategies and implementing other safety measures to reduce the risk of airborne transmission of infections, ultimately leading to safer indoor spaces during pandemics.

By identifying hotspots where these particles tend to accumulate or linger, it becomes possible to strategize the placement and operation of ventilation and air purifiers to mitigate the risk of airborne transmission.

Furthermore, CFD can inform the design of effective mitigation measures such as air purifiers, barriers, and optimized airflow pathways. By simulating different configurations and operational strategies, researchers can evaluate their efficacy in reducing the concentration of infectious aerosols in critical areas. This data-

driven approach aids in developing guidelines for building layouts, ventilation rates, and occupancy limits that collectively enhance the overall health and safety of indoor environments. Ultimately, the use of CFD in the context of pandemic planning not only supports immediate response efforts but also contributes to long-term resilience against future airborne health threats.

4.1.6 Software used

This study utilises two distinct CFD software:

- OpenFOAM (openfoam.org) and
- Palm (palm.muk.uni-hannover.de/trac).

Each has its unique advantages and disadvantages.

OpenFOAM (Open Field Operation and Manipulation) is an open-source software package used extensively in CFD. It provides a comprehensive suite of tools for the simulation of fluid flow, heat transfer, and associated phenomena.

OpenFOAM is built on C++ and utilizes object-oriented programming principles to create a flexible and extensible framework. The software employs the finite volume method (FVM) to discretize partial differential equations (PDEs) that govern fluid flow. This approach divides the computational domain into a finite number of control volumes, and the integral form of the governing equations is applied to each volume, ensuring conservation laws are satisfied.

In the context of indoor air applications, OpenFOAM proves particularly valuable due to its ability to handle the complexity of turbulent flow within confined spaces. The software supports several turbulence modelling approaches, including:

- RANS: Suitable for steady-state simulations where the focus is on the average flow characteristics over time. It simplifies the modelling process by solving the time-averaged equations of motion. Although originally not intended for this purpose, it can also be applied to unsteady simulations as an unsteady RANS (URANS).
- DES: A hybrid approach that combines the strengths of RANS and LES, providing a balance between computational efficiency and accuracy in capturing transient flow features.
- LES: Ideal for simulating unsteady flow phenomena by directly resolving large-scale eddies and modelling the smaller scales. This approach requires significant computational resources but yields highly detailed results.

OpenFOAM stands out as a powerful tool for CFD simulations, offering flexibility, extensive capabilities, and a strong support community. Its application in indoor air turbulence modelling demonstrates its potential to address complex flow scenarios, making it an indispensable resource for researchers and engineers alike.

Palm software, an advanced tool in the realm of CFD, offers a robust platform for simulating and analysing fluid flow, heat transfer, and related phenomena. Developed with a focus on flexibility, usability, and efficiency, Palm has become a vital resource for researchers and engineers aiming to solve complex fluid dynamics problems. Unlike traditional CFD software, Palm is designed to support massively parallel computations, making it particularly suitable for high-performance computing environments.

The development of Palm software traces back to the early 2000s, when the need for more scalable and efficient CFD tools became apparent. Traditional CFD tools, while powerful, struggled to handle the increasing complexity and scale of modern simulations. Palm was conceived to address these limitations, offering a platform that could efficiently utilize the growing computational power of parallel processors. Over the years, Palm has evolved through continuous development and contributions from the global CFD community, integrating cutting-edge algorithms and techniques to enhance its capabilities.

Palm software is distinguished by several core features that set it apart from other CFD tools:

- Massively parallel computation. One of the standout features of Palm is its ability to perform massively parallel computations. This capability is crucial for handling large-scale simulations that require significant computational resources. Palm's architecture is optimized to run on high-performance computing clusters, enabling users to solve complex
- High-resolution simulations. Palm supports high-resolution simulations, providing detailed insights into fluid flow and heat transfer phenomena. This capability is valuable for applications that require accurate predictions of complex, unsteady flows, such as turbulence and multiphase flows.

In indoor air simulation, Palm software excels in modelling the intricate dynamics of airflow, temperature distribution, and contaminant dispersion within enclosed spaces. By employing high-resolution CFD, researchers and engineers can simulate various ventilation strategies and their impacts on air quality and thermal comfort. This capability is crucial in designing HVAC systems, optimizing energy efficiency, and ensuring compliance with health and safety standards. Palm's ability to handle complex geometries and transient conditions makes it an indispensable tool for improving indoor environments in residential, commercial, and industrial buildings.

4.1.7 Research within this project

This research involves the use of OpenFOAM with RANS and DES, as well as Palm with LES. It primarily focuses on passive scalar simulations, though it also includes some studies using Lagrangian models.

4.1.8 References

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4.2 Sensor network for detecting dispersion of particles at indoor conditions

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Abstract: Dispersion of small aerosol particles within the room provide a good indicator of the air movement and mixing. The ability of PM sensors to observe the mixing of air and dispersion of pollutants was tested in VTT big chamber (55 m3) experiments with a network of vertically and horizontally divided aerosol particle sensors. Sensors were used to detect the spreading of generated particles using either replacement or mixing ventilation. The results gained from sensors were compared to the modelled particle concentrations. The results of comparison were utmost important for the validation of models. This article describes the sensor network and shows examples of results.

4.2.1 Introduction

Low-cost sensors have provided a viable means to construct a dense measurement network to detect temporal and spatial variation of pollutants. Sensor networks have been widely utilized in ambient studies, chamber studies and indoor studies (e.g. Kuula et al., 2017, 2020). When properly tested and calibrated, the particle sensors can provide information about the atmospheric particle concentrations. Although the low-cost sensors cannot selectively detect microbes, they can give important information how the particles disperse in a space due to ventilation.

In this study sensors were utilized in VTT big chamber (55 m3) experiments, where a network of vertically and horizontally divided aerosol particle sensors (9 x Sensirion, 5 x Airlyse sensors, 3 x Air0 sensors) were used to detect the spreading of generated particles. In the room either replacement or mixing ventilation was used. The aim was to simulate a situation where a source of viruses is in the room generating viruses and see how the ventilation type and efficiency influences the spreading. This chapter describes the sensor network and shows examples of results.

4.2.2 Sensor network

Figure 1. shows the locations of the sensors and experimental setup including PM source, used heat source (cylinder or radiator) as well as incoming air and exhaust

locations. The Sensirion particle sensors were installed to the chamber spread between different heights (0.5, 1.5 and 2.5m) and distances from the source as shown in figure 1. The Swatcher (Airlyse) and Air0 sensors were installed in the walls, at approximately to the breathing height (1.5m). The aim was to create comprehensive network to detect the spatio-temporal variation of the particles. Figure 2 shows the chamber and sensor installations.

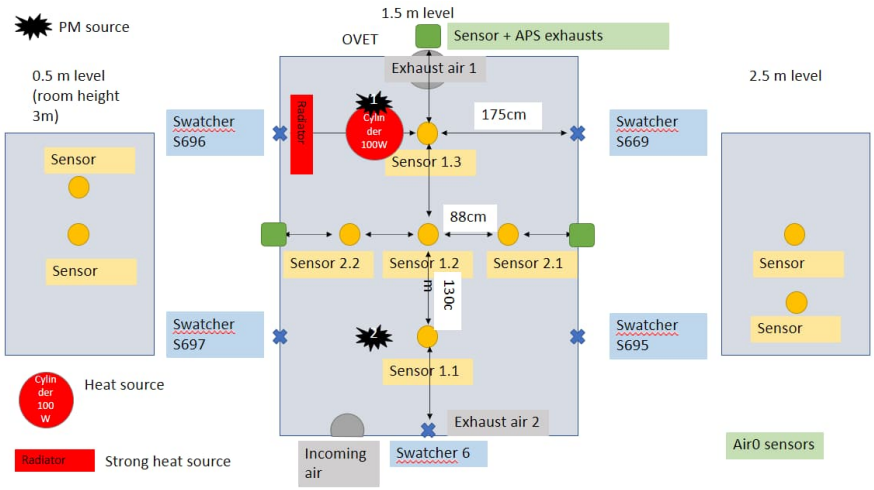

Figure 1. The locations of sensors at three different levels (0.5m left, 1.5m middle, 2.5m right)

Figure 2. The chamber during installations

A list of sensors and reference level measurement instruments used to detect the dispersion of particles is shown in table 1. SMPS and APS were used to measure particle size distributions between 10nm and 20µm, CPC particle number concentrations and WIBS size distribution of scattering/fluorescence.

Table 1. Measurement instruments used to detect the dispersion of particles.

INSTRUMENT	**MEASURED PARAMETER**	**TIME-RESOLUTION**	**FLOW (LPM)**
TSI SMPS + CPC 3776	Size distribution (10-500nm)	1min	1.5
APS X 2	Size distribution (0.5-20 µm)	1 sec	1
CPC X 4	Number concentration	1 sec	0.3
WIBS	Scattering / fluorescence, size distribution (0.5-50 µm)		0.3
9 SENSIRION PM SENSORS	Size range ~300 nm - 1.3 µm (scattering, T, RH)	1s	~0.3
5 Airlyse sensors	T, RH, TVOC, CO2, PM1.0, PM2.5, PM4.0, PM10.		
2 Alphasense sensors (OPC-N3, OPC-N2)	T, RH, TVOC, CO2, PM1.0, PM2.5, PM4.0, PM10.		
3 Air0 sensor	T, RH, TVOC, CO2, PM1.0, PM2.5, PM4.0, PM10.		

A set of experiments with different ventilation systems, ACHs and radiator powers as described in table 2 was conducted. In all experiments a bubbler was used to generate particles from DES. In each experiment the aerosol generation was turned on at the beginning of the experiment. After the situation was observed to be stable, particles were generated for 1-2h and then the generation was turned off. Altogether the experiments lasted from 2-4h, depending on used ACH.

Table 2. The experiment details.

Exp	Ventilation	start	stop	Interval (h)	Repeats	exhaust	ACH	Q_incoming (l/s)	Q_exhaust(l/s)	Mixing plate	Q_generation (l/min)	Radiator	Radiator power (W)	incoming air
1	Mixing	19.05.2022 00.00.00	-	2	3	Front	5	75	75	Y	1,5	Y	205	Back
2	Mixing	20.05.2022 00.00.00	-	5	3	Front	2	30	30	Y	1,2	Y	205	Back
3	Mixing	23.05.2022 14.00.00	24.05.2022 08.00.00	3	3	Front	2	30	30	Y	0,5	Y	205	Back
4	Mixing	24.05.2022 22.00.00	25.05.2022 16.00.00	3	3	Front	2	30	30	N	1,2	Y	205	Back
5	Mixing	25.05.2022 16.10.00	26.05.2022 10.10.00	3	3	Back	2	30	30	N	1,2	Y	205	Back
6	Mixing	30.05.2022 14.30.00	31.05.2022 08.30.00	3	3	Back	5	75	75	N	1,5	Y	205	Back
7	Mixing	31.05.2022 12.07.00	01.06.2022 06.07.00	3	3	Front	5	75	75	Y	1,5	Y	205	Back
8	Replacement	01.06.2022 10.14.00	02.06.2022 04.14.00	3	3	Front	5	75	75	N	1,5	Y	205	Back
9	Replacement	02.06.2022 11.45.00	03.06.2022 05.45.00	3	3	Front	2	30	30	N	1,5	Y	205	Back
10	Replacement	03.06.2022 16.55.00	04.06.2022 10.55.00	3	3	Front	2	30	30	N	1,2	Y	205	Back
11	Replacement	06.06.2022 14.30.00	07.06.2022 08.30.00	3	3	Front	5	75	75	N	1,5	N	0	Back
12	Replacement	07.06.2022 15.30.00	08.06.2022 09.30.00	3	3	Front	5	75	75	N	1,5	N	0	Back
13	Replacement	08.06.2022 11.53.00	09.06.2022 05.53.00	3	3	Front	5	75	75	N	1,5	Y	205	Back
14	Replacement	09.06.2022 12.35.00	10.06.2022 06.35.00	3	3	Front	10	150	150	N	1,5	Y	205	Back
15	Mixing	10.06.2022 11.17.00	11.06.2022 05.17.00	3	3	Front	10	150	150	Y	1,5	Y	205	Back
16	Mixing	13.06.2022 13.30.00	14.06.2022 07.30.00	3	3	Front	10	150	150	Y	1,5	N	0	Back

4.2.3 Results/Findings

Figure 3 shows the example timeseries of particle number concentrations and room temperature during the experiment 4 (mixing ventilation) and 9 (replacement ventilation). In can be seen that the sensors were able to follow the concentrations of generated particles and the influence of the ventilation to spatial and temporal variation of particles was clearly observed

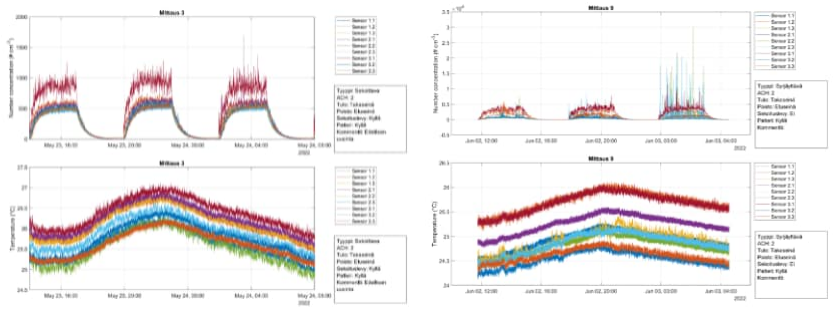

Figure 3. The particle concentrations (#/cm3) and temperature timeseries during example experiments when particles were generated for a certain time period and then stopped. The experiment was repeated three times.

4.2.4 Conclusions

Sensors provided a viable means for detecting the spatiotemporal variation of the particles in the chamber and enabled direct measurement of influence of ventilation to the particle concentrations in the air. However, we note that the sensors only

measure the concentration of total particles, not microbes. Also, it should be noted that optical particle sensors are not able to observe particles below 300nm, thus it is important to generate large enough particles. The measurement results were used in the model development and the results of the comparison with the model are shown in the following chapters.

4.2.5 Acknowledgements

We acknowledge all the researchers from TAU, FMI, VTT, TAMK and companies who participated to the planning and during the campaigns to the measurements.

4.2.6 References

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4.3 LES-modelling of aerosol dispersion in test chamber setup – model validation study

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Abstract: This validation study uses large eddy simulation (LES) to model indoor aerosol particle dispersion, comparing results with test chamber measurements. It highlights the challenge of modelling indoor air flows that are largely dominated by weak free turbulence, which is sensitive to modelling errors. The study demonstrates that, with sufficient resolution, LES accurately resolves indoor ventilation flow fields and dispersion of fine aerosol particles, validating LES's utility and reliability in pathogen exposure and air hygiene investigations.

4.3.1 Introduction

Airborne transmission of pathogens is a complex phenomenon that is fundamentally rooted in the dispersion process occurring in indoor air. The rate at which pathogens are spread, diluted and ultimately removed from a given indoor space constitutes the necessary precursor information needed by subsequent exposure and risk analysis. Indoor flows, which are responsible for carrying out the dispersion process, are characterized by weak free turbulence which is locally energized by jets from ventilation system inlets and buoyant plumes from thermal elements. The resulting turbulent flow system is difficult to model correctly because the weak flow system is highly sensitive to modelling error. Despite being demanding, computational techniques, such as CFD, are widely utilized in making predictions and designing remedies concerning airborne transmission risks or related outcomes. In recognition of known modeling challenges and the sensitive nature of risk assessments, it is essential to demonstrate that the models used are able to capture and predict the relevant phenomena accurately and reliably. Thus, it is necessary to demonstrate model validation. Large-eddy simulation (LES) is one of CDF techniques and has a wide range of different applications, being the most effective tool also for indoor air studies. This section presents a validation campaign featuring aerosol dispersion experiments at VTT test chamber and LES simulation results with a 3d PALM LES model that closely replicates the conditions at the chamber (e.g. ventilation system, heat and particle sources).

4.3.2 LES model setup for VTT Chamber

The employed LES model is a special indoor version of the PALM LES model, well documented in Auvinen et al. (2022) and references therein. This 'indoor-PALM' resolves the indoor air turbulence and provides detailed and precise information on aerosol dispersion. The modeling domain, replicating the VTT test chamber

presented in chapter 4.2, is a rectangle with the same dimensions as the experimental chamber. Air ventilation inlet and outlet were placed correspondingly as in the chamber. In the model, the heating element and aerosol source were slightly simplified solid structures (rectangles instead of more cylinder-formed shapes), but of their realistic sizes. Figure 4.5.1 illustrates the chamber set up as in the model.

The chamber features one inlet and outlet whose volume flow rates $Q_{in}=Q_{out}=U*A_d$ were specified by imposing fixed velocity across the ducts area A_d. The inlet temperature is set constant at T_{in}=293C whereas the room is equipped with two thermal sources, one heating element with 200W thermal output and one manikin with 100W output. Here, it is assumed that all thermal power is converted to air temperature, ignoring the effect of radiation. This simplification was justified by performing otherwise identical simulation but reducing the thermal power by 25% and examining the changes in the aerosol dispersion outcomes. No meaningful difference was observed in the results, highlighting how weakly thermal energy is converted to mechanical turbulence which is primarily responsible for carrying out the dispersion. Table 1 below summarizes the boundary conditions for the two cases considered in this validation study.

Table 1: Relevant boundary conditions for the chamber modelling cases

Ventilation rate (ACH)	2	5
Volume flow rate, Q_{in}/Q_{out} (m^3/h)	110.3	275.6
Inlet temperature, T_{in} (K)	293	
Manikin heat flux, q_m (W)	100	
Radiator heat flux, q_r (W)	200	
Wall boundary condition, momentum	No slip, wall function	
Wall boundary condition, temperature	Adiabatic	

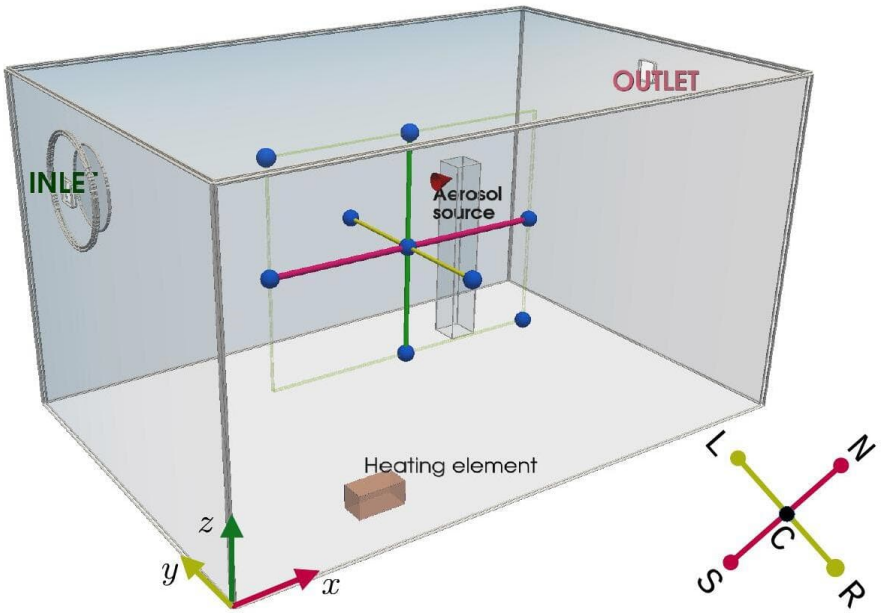

Figure 1: A schematic picture of measurement chamber set up created for the LES-model. The coordinate system convention (north/south, left/right) at the x,y -plane for the sensor locations is exhibited in the bottom right corner. The elevation of the sensors in the z -direction are denoted by LO, MD, HI (low, middle, high).

4.3.3 Validation of the LES model against experimental measurements

LES is a turbulence-resolving modelling approach, which requires substantial computational power. To optimize the balance between the computational demand and accuracy of the result, it resolves the energy-containing turbulent eddies which are relevant to the application and models the smaller scales whose behavior conform to parametrization. It is important for the user to understand what are these relevant turbulent scales that must be resolved by the model. It was already known from previous indoor studies (e.g. Auvinen et al., 2022), that ordinary mixing type ventilation flow system requires the resolution of centimeter-scale, depending on the geometry of the inlet ducts and thermal elements inside the room. Here, two different resolutions, 1 and 2 cm, were used in the model and compared with the measurements.

From the modeled time series of 3d particle concentration field inside the room, the surrounding of 9 measurement inlets (Figure 1) were taken into more detailed analysis. As expected, both measurements and model show a rapid increase of particle concentration in each 9 locations during the first 30 minutes (Fig. 2). After that the particle concentration started gradually to saturate. This phenomenon was

captured by both 1 and 2 cm modelling resolutions indicating that the model can represent the environmental conditions. However, by using 2 cm resolution the turbulence inside the room cannot be resolved well enough to fully replicate the measurements - stratification is too strong causing too weak dispersion. This can be seen when comparing the height of the time series curves in Figure 2. With 2 cm resolution the values in different heights follow similar patterns while measurements show maximum values close to the roof. This can be accurately modelled by choosing the finer 1 cm resolution in the model in this specific case as shown in Figure 2.

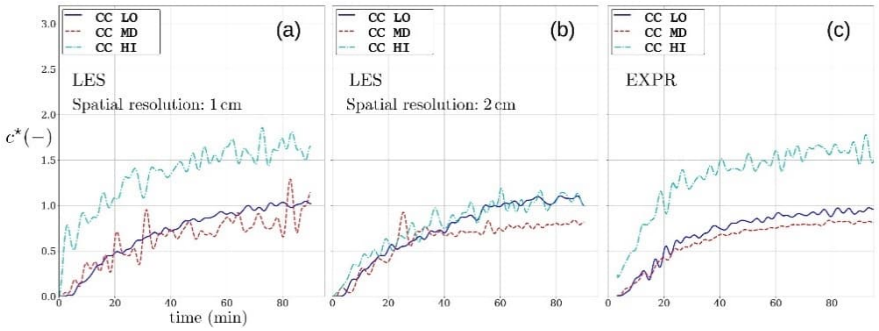

Figure 2: Fourier filtered time series of normalized aerosol particle concentration obtained from three different sensor heights (dark blue: low, red: middle, cyan: high) at the center of the chamber. Figure (a) and (b) depict the modelling results with 1 and 2 cm resolution, respectively whereas (c) exhibits the measured time series.

Modelling and measurements were also compared quantitatively by calculating statistical performance measures: the root normalized mean square error (RNMSE), the fractional bias (FB), the fraction of predictions within a factor of two of observations (FAC2), and the correlation coefficient (R). Acceptable bounds for pollutant dispersion validation metrics were set according to Chang et. Hanna (2004):

$$\{0\} < RNMSE < 1.2$$
$$\{0\} < |FB| < 0.3$$
$$0.5 < FAC2 < \{1\}$$
$$0.8 < R < \{1\}$$

where { } indicates ideal value.

Tables 2 and 3 depict these validation metrics averaging over each local comparison between model and experimental time series. Two cases with different ventilation rates, 2 and 5 air changes per hour (*ACH*), are considered herein. In Table 2, the validation results are presented for the fine model with 1 cm spatial resolution while Table 3 has the results for the coarse model with 2 cm

resolution. A detailed, sensor-by-sensor validation analysis will be later published in a scientific journal (Auvinen et al., 2024 in prep.).

All the validation metrics are well within the acceptable bounds, as laid out by Chang and Hanna (2004), for air quality predictions, and especially R showing linear dependence between the measured and modelled values. The most robust measure, FAC2, is close to optimal value. Both experimental and modeled concentration time series feature high-frequency turbulent fluctuations, which strongly affect RNMSE values. These fluctuations are sensitive to sensor characteristics (which are partly unknown) and individual simulation realizations (which are random at nature) and therefore it is desirable to eliminate their influence all together. This is achieved by applying Fourier filtering, cutting out all high-frequency oscillations from both signals. The case with higher ventilation exhibits better agreement between the model and experiment except for the R which turns slightly lower. Coarser (2 cm) resolution shows slightly impaired results (Table 2). Especially FB, which reflects systematic deviation between the signals, becomes notably worse with coarser resolution. This is visible in Figure 2 (b) where the sensor at highest elevation (HI) does not capture the effect of the thermal stratification. Still, all the metrics are acceptable according to the criteria. Here, the increase in ACH only improves FAC2. Overall, based on statistical metrics, the agreement between the model and the measurements is very good.

Table 2: Global validation metrics from the comparison between LES -results and experimental measurements. The spatial resolution of the LES model is 1 cm.

Δx = 1 cm	**<RNMSE>**	**<|FB|>**	**<FAC2>**	**<R>**
ACH=2	0.176	0.152	0.911	0.943
ACH=5	0.163	0.107	0.969	0.930

Table 3: Global validation metrics as in Table 1. Here, the spatial resolution of the LES model is 2 cm.

Δx = 2 cm	**<RNMSE>**	**<|FB|>**	**<FAC2>**	**<R>**
ACH=2	0.290	0.219	0.860	0.928
ACH=5	0.342	0.288	0.886	0.856

4.3.4 Conclusion

A validation campaign has been carried out comparing PALM LES modelled and experimental aerosol concentration time series in close controlled test chamber. Two model resolutions are utilized to establish how sensitive the turbulence resolving LES model is to spatial resolution. Based on several statistical metrics, both resolutions show a good agreement between the modelled and measured

values. By using fine, 1 cm resolution, also strong stratification caused by heat elements in the room, can be generated exactly by the model.

4.3.5 References

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Auvinen M, Izbassarov D, Grönholm T, Hellsten A. (2024, in prep.). Modeling dispersion by indoor turbulence with LES – Validation study. To be submitted to Physics of Fluids.

Chang, J. C., & Hanna, S. R. (2004). Air quality model performance evaluation. *Meteorology and Atmospheric Physics*, *87*(1), 167-196.

4.4 LES-model development for study on air hygiene fundamentals

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Abstract: The pathogen dispersion driven by indoor turbulence has been studied extensively by means of high-resolution LES modelling. It is shown that the basic indoor ventilation system properties, such as ventilation rate, room size, and the level of turbulent mixing in the flow system characterize the indoor dispersion. Although the existing analytical prediction fail to forecast the dispersion with a sufficient precision, the deviations do show a systematic trend. This opens the possibility to introduce parametrizations that improve the analytical model.

4.4.1 Introduction

In this study, the main objective is to establish generalizable fundamentals and dependencies about pathogen dispersion by indoor turbulence. In this context, the flow within an indoor space is considered as a *system* which has properties that can be characterized quantitatively in terms of well-established ventilation system attributes (e.g. room size, ventilation flow rate). The goal is to uncover how the processes governing pathogen dispersion outcomes are influenced by these ventilation flow system properties. This kind of analysis necessitates a modeling approach that is both sufficiently generic and numerically accurate to resolve the relevant flow physics in a manner that is reliable and not prone to application-specific peculiarities. Thus, the conducted numerical experiment has been designed accordingly allowing generalizable conclusions to be made concerning air hygienic performance of different indoor flow systems. The ambition is to pave the way for a universal framework for basic analysis in the field of air hygiene in the context of airborne transmission of pathogens.

4.4.2 LES model and simulation matrix

A comprehensive series of LES simulations depicting the evolution of a pathogen concentration field arising from a local source (like an infected individual). Figure 1 below illustrates the three different room geometries used in the study. Figure 1 (a) depicts the base geometry, which is a digital twin of a real dental treatment room with volume V=45 m^3, featuring a conventional mechanical ventilation system and a neutral thermal environment (close to uniform vertical temperature distribution) giving rise to a mixed-type ventilation flow system. Some basic furniture is also included in the model in accordance with the real twin room. The larger rooms in Figure 1 are integer multiples of the base geometry, room (b) being twice and (c) four times the size of (a). Their respective volumes are 90 m^3

and 180 m^3. The computational models feature 2 cm spatial resolution determined via numerical experiments to provide reliable predictions about the evolution of the mean concentration field.

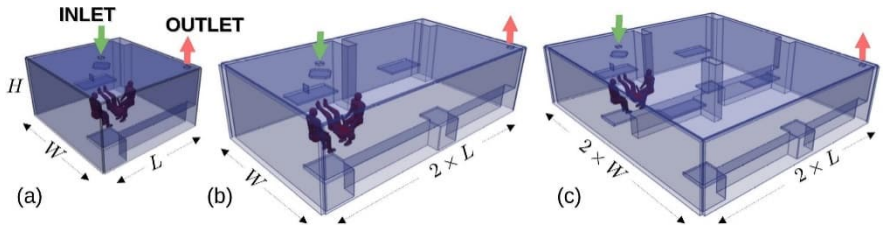

Figure 1: Visualizations of the different LES -model geometries and their inlet/outlet locations. The room (a), which represents the base geometry, has dimensions H=2.4 m, W=4.6 m, and L=4.22 m. The larger rooms (b) and (c) are two and four tmies the size of (a).

All rooms feature a similar mechanical ventilation system implementation having one inlet and one outlet. The momentum and aerosol concentration boundary conditions are implemented the same way as in Chapter 4.5. The thermal treatment differs such that the walls are set at constant temperature T_w=294 C whereas the flow temperature at inlet is at T_{in}=292 C. These values are adopted from the real operation room and result in nearly uniform thermal conditions within the room.

The room geometries include three manikins staging a dental operation with a dentist, an assistant and a patient. Preliminary tests were carried out where the manikins were assigned a modest heat flux. The subsequent results revealed that the volume-averaged aerosol concentration results had no discernible sensitivity to this thermal modeling detail and therefore the manikins are set to have the same constant temperature as the walls. The constant aerosol concentration source is placed in front of the patient manikin with a weak vertical upward jet to enhance the initial dispersion. The location of the aerosol source may at times play a crucial role in determining the evolution of the concentration field especially if it is too close to the outlet. However, in this setup, it is deemed critical that the source is located such that the dispersion outcome is essentially dictated by the flow system (whose properties are under examination) and not by the placement of the pathogen source.

The numerical study encompasses a thorough matrix of simulations with different indoor ventilation conditions characterized by ventilation volume flow rate, the room size and by the amount of mixing added into the indoor flow system (for example by an external fan or strong thermal elements). The size of the computational case matrix is N_Q x N_V x N_P=45 where N_Q=5 is the number of ventilation rates (Q_e={1,2,3,4,5} V/h, in terms of *ACH* or room volumes per hour), N_V=3 is the number of different room sizes (V={45,90,180} m3) and N_P=3 indicates different augmented mixing power levels (P={0,5,10} net wattage). Each case is

computed sufficiently long time to allow the concentration level to approach its asymptotic state.

4.4.3 Dimensionless analysis on evolution of mean aerosol concentration

The performed analysis is firmly rooted in the well-known analytical solution for the evolution of concentration within a ventilated room

$$\langle c \rangle = (G/Q_e)\left(1 - e^{(-(Q_e/V)t)}\right)$$

where $\langle c \rangle$ is the mean aerosol concentration, G is the generation rate of aerosols, Q is the volume flow rate of the ventilation, V is the volume of the room and t is time. This analytical solution has many desirable properties as it identifies the level of the asymptotic concentration level (G/Q_e) and the time scale of the concentration growth (Q_e/V) which are central concepts in the context of air hygiene. In effort to preserve these favorable analytical aspects and establish a universal coherence to the analysis, the problem is cast to a dimensionless form. This is achieved by defining a dimensionless concentration $\langle c^+ \rangle = \langle c \rangle (Q_e/G)$ and time $t^+ = (Q_e/V)t$. The analytical solution thereby becomes

$$\langle c^+ \rangle = (1 - e^{(-t^+)})$$

which poses as a standardized growth curve whose asymptote and time scale are both equal to unity. See Figure 2 below.

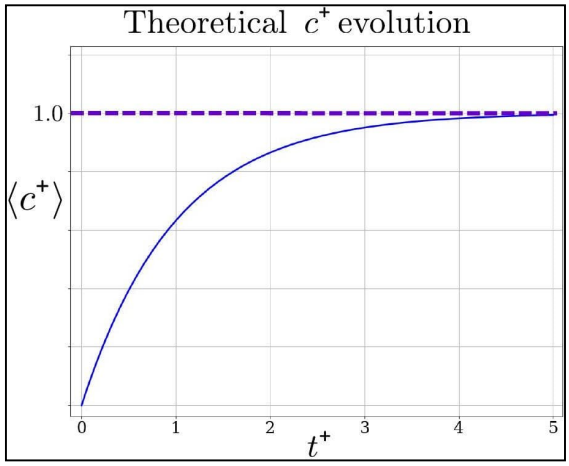

Figure 2: Plot depicting the dimensionless analytical evolution curve for the mean pathogen concentration in a room. By casting different pathogen concentration results into dimensionless form, different cases can be analysed in terms of how close to the analytical ideal they behave.

By scaling the obtained concentration and time values to obtain $\langle c^+ \rangle$ and t^+ for all simulation cases, makes them directly comparable although the actual realizations can be drastically different. The obtained dimensionless time series

warrant a somewhat unconventional interpretation as they convey the performance of the system in terms of how much the considered dispersion outcome deviates from the analytical ideal in Figure 2.

Figure 3 below illustrates the range of dimensionless evolution curves from the LES analysis, highlighting the two extremes – the cases that are closest (blue) and farthest to the analytical. The blue curve, representing the 'most ideal' is obtained from the case with smallest room, having the lowest air change rate ($ACH = Q_e/V = 1$) and equipped with a fan generating 10 W of net mechanical mixing power. This system's dispersion evolution closely follows the analytical model both in terms of expected final concentration level and time scale. However, $ACH = 1$ is rather low ventilation rate, so the case does not represent a good outcome in terms of air hygienic performance, but the adherence indicates that its behavior is readily predictable. In contrast, the yellow curve in Figure 3 represents the case that deviates from the analytical prediction the most. This case features the largest room, the highest ventilation rate ($ACH = 5$) and no augmented mixing power. This case exhibits over 100% higher final concentration than the analytical expectation and overestimates the time scale significantly revealing how the analytical idealization concerning the mixing rate is unrealistically fast. In reality, the rate of dispersion is dictated by the indoor turbulence, and this process involves time scales that cause the evolution of the concentration field to manifest with longer time scales than the analytical model predicts.

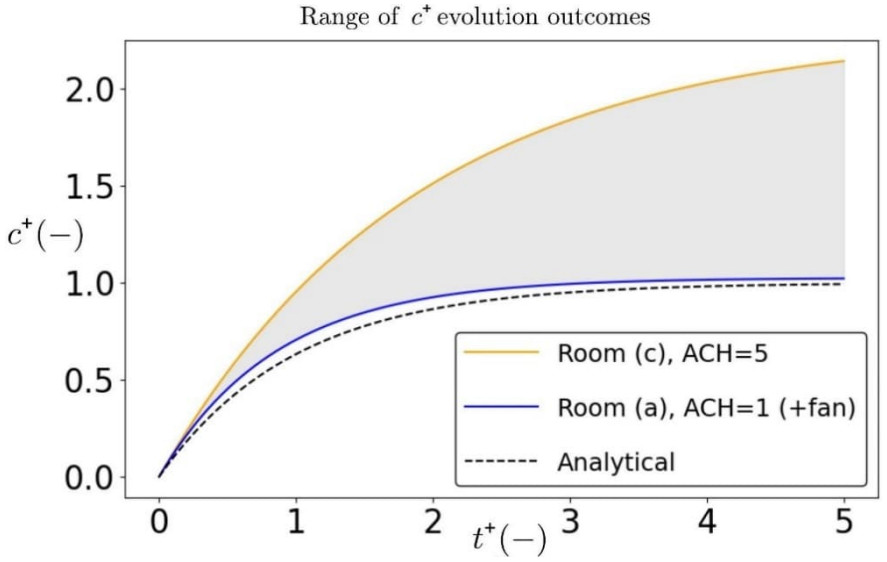

Figure 3: Dimensionless evolution curves obtained from the series of LES analysis with different ventilation system specifications. The range of outcomes is shown highlighting the two cases that deviate the least (blue line) and most (yellow line) together with the analytical expectation (black dotted line).

The other cases populate the grey space between the two extremes very evenly, demonstrating some basic dependencies explaining the deviations between the analytical expectation and the modelled realizations. For example, the higher the volume flow rate (or *ACH*) and the larger the room in which the dispersion occurs, the more pronounced the deviations from the analytical predictions are.

4.4.4 Conclusions

This study examines how the basic indoor ventilation system characteristic influence the air hygienic performance of indoor spaces. Here, air hygiene relates to the indoor flow system's ability to control and reduce pathogen concentration levels within a room in a generalizable manner. The study carries out a series of high-resolution LES analysis, providing strong evidence that the indoor dispersion processes can be systematically characterized by the basic indoor ventilation system properties, such as ventilation rate, room size and the level of turbulent mixing in the flow system.

This study also establishes that the evaluation of indoor flow systems' air hygienic performance can have a universal basis which is not sensitive to application-specific details. Although the dispersion outcomes do not follow the analytical predictions with sufficient precision, the deviations do show a systematic trend which opens the possibility to introduce parametrizations that improve the analytical model. This is the topic of the upcoming Chapter 4.7.

4.4.5 References

Auvinen M, Kuula J, Grönholm T, Sühring M, Hellsten A. (2022). High-resolution large-eddy simulation of indoor turbulence and its effect on airborne transmission of respiratory pathogens-Model validation and infection probability analysis. *Physics of Fluids* (1994), 34(1), 015124. doi: 10.1063/5.0076495

Chang, J. C., & Hanna, S. R. (2004). Air quality model performance evaluation. *Meteorology and Atmospheric Physics*, *87*(1), 167-196.

4.5 Parametric model for pathogen dispersion and infection risk analysis based on LES modelling

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Abstract: Analytical models for indoor airborne transmission risk assume perfect mixing, leading to optimistic ventilation efficiency estimates. In this work, a new parametric model, based on extensive LES simulations, is derived. This model reduces errors inherent to the analytical solution. It accounts for various ventilation solutions, providing realistic predictions of pathogen concentration evolution indoors. This cost-effective tool aids in designing air hygienic ventilation systems and assessing airborne transmission risks in indoor environments.

4.5.1 Introduction

Time and space averaged analytical equations are often used to model the concentration of some harmful compounds indoors (Auvinen et al., 2022). However, the averaging or integrating over the whole room assuming the perfect mixing often provide misleading information about the ventilation efficiency and pathogen concentration. On the other hand, computationally expensive and time-consuming dispersion modelling is in practice impossible to use in routine risk assessment or ventilation design work. Therefore, a new, simple-to-use parametric model has been derived to provide fundamental information governing pathogen dispersion and therefore also airborne transmission indoors. It is based on a large sample of indoor LES dispersion simulations which are run with a standardized setup and analysed in a dimensionless form.

4.5.2 Development of improved analytical model for indoor air

As a starting point, the parametric model utilizes the well-known analytical solution for mean concentration evolution in a room with idealized (instantaneous) mixing conditions

$$\langle c \rangle = (G/Q_e)\left(1 - e^{(-(Q_e/V)t)}\right)$$

where $\langle c \rangle$ is mean concentration of the compound (#/m³), G is emission rate (#/s), Q_e is effective removal rate (m3/s) and V is volume of the room (m³). As the main weakness, this basic, widely used analytical equation relies on an unrealistic assumption of ideal dispersion rate, and therefore provides only a very coarse description of the indoor air concentration (see chapter 4.6). To resolve the discrepancy between the model and reality, more informatic parametrization related to dilution and dispersion was needed.

Thus, the next step towards the more realistic model was to simplify the analysis and convert the traditional analytical model (Eq. 1) into a dimensionless form as in chapter 4.6 by defining

$$\langle c^+ \rangle = \langle c \rangle (Q_e / G) \text{ and } t^+ = (Q_e / V)t,$$

yielding

$$\langle c^+ \rangle = \left(1 - e^{(-t^+)}\right)$$

Then, two 'correction' parameters $\alpha(Q_e, V, P)$ and $\beta(Q_e, V, P)$ were added into the equation. They both are functions of the basic parameters characterizing indoor ventilation systems: the ventilation volume flow rate Q_e, volume of the room V, and added mixing power to the flow system (for example by a fan) P. The main purpose of the modified equation is to account for the effect of real, non-ideal mixing conditions inside the room (as assumed by the analytical formulation). Thus, the 'corrected' analytical solution becomes

$$\langle c^+ \rangle = \beta\left(1 - e^{(-\alpha t^+)}\right)$$

where α corrects the time scale of the pathogen concentration evolution and β corrects the asymptotic concentration level. The objective is to parametrize these two correction factors such that they can describe the variability in the system behavior as demonstrated by Figure 3 in chapter 4.6.

To find the physically relevant values for α and β, a new variable, mixing metric (M) was introduced. It describes the flow system ability to dilute concentration peaks. Based on a large number of LES simulations (see chapters 4.5 and 4.6) the best fit for M characteristic to indoor air as a function of V, Q, and P was found. Stemming from M the standard deviation of the 3D concentration field ($\sigma_c^+(Q_e, V, P)$ was derived to characterize how the concentration of some compound is distributed inside the room. Finally, the correction terms α and β are expressed as combined closed-form functions whose coefficients and exponents are searched via curve-fitting optimization process. The equations for α and β have following form

$$\alpha(V, Q, P) = a_3 \mathrm{M}^* + a_2 Q^* + a_1 V^* + a_0$$
$$\beta(V, Q, P) = b_3 \mathrm{M}^* + b_2 Q^* + b_1 V^* + b_0$$

Including dimensionless terms for mixing (M*) ventilation volume flow rate (Q*), and dimension of the room (V*). Typical values for β and α lie between $1 < \beta < 2.2$ and $0.7 < \alpha < 1.4$ depending on the configuration and the conditions. This roughly means that after some time, when the asymptotic level inside the room has reached, the pathogen concentration can reach be up to 2 times higher level than the commonly used analytical model estimates.

In addition to a physically more accurate description of the dispersion, the new parameterization can take into account different ventilation system configurations. These are, for example, the cases like 1) one inlet, one outlet system, 2) improved

system with multiple inlets and multiple outlets, and 3) distributed mixing system consisting of multiple fans or momentum sources inside the room. This enables the use of the model also in the planning of the ventilation system for the new buildings or during the renovations.

A detailed description of the new parametrization derivation is out of scope of this project report but will be published separately in a scientific journal (Auvinen et al., in preparation).

4.5.3 Conclusions

The existing simple and widely used parametrization for indoor air has shown to be only a coarse description of the situation and typically underestimates the concentrations. Based on numerous LES-runs, the parameterization has been developed further to better take into account turbulent mixing and dispersion in indoor environments. The new parametric model provides information about the spatial distribution of the 3D concentration field and via that a more realistic risk factor can be determined for the space. The new model can also account for different ventilation systems from single to multiple inlets and outlets and also an increased mixing by using fans. It provides a simple and effective tool when planning new buildings or renovating old systems in a cost-efficient way.

4.5.4 References

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Auvinen et al. (in preparation). Fundamentals of parametrized pathogen dispersion and risk analysis indoors. Article is to be submitted.

4.6 An air filter in indoor air flow simulations

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Abstract: Detailed flow simulation of the filter material used in air purifiers requires considerable computing capacity and is therefore not feasible in a general application. Incorporating the air purifier into a computational fluid dynamics (CFD) simulation of indoor air flows necessitates a technique that can remove a predefined portion of contaminants from the airflow passing through the filter, without needing to model the inner structure of the filter. This chapter describes how the application implemented in this project for OpenFOAM software works.

4.6.1 Introduction

Computational fluid dynamics (CFD) simulation typically demands substantial computing power, especially when dealing with large-scale differences as for example in indoor air flows. For instance, the calculation domain might be very large yet include small geometric features.

The filter material in the air purifier is composed usually of extremely fine fibres. As a result, incorporating the air purifier into simulations of room-wide airflow would create significant discrepancies in length scales and thus requires a very large computing capacity (Yue et. al. 2016). Consequently, this approach is not feasible in most scenarios.

OpenFOAM ranks among the most widely utilized open-source CFD software. In this study, modifications have been made to the ParticleCollector application (CloudFunctionObject) within OpenFOAM to allow for the input of a measured or otherwise pre-determined filter efficiency curve. This curve is provided as an easy-to-use table of points, and the tool interpolates the required intermediate values. The filter geometry can be specified either as a circular disc or any arbitrary STL surface. The new modified application is called ParticleFilter.

It should be noted that the application now implemented can be used regardless of the method by which the filter itself works (electrical, mechanical, etc.), as long as its separation efficiency is known (Hou et. al. 2019).

4.6.2 Methods

Figure 1 illustrates a separation efficiency of a real-world air filter. Notably, the efficiency reaches its minimum for particles approximately 0.3 µm in diameter, whereas it is significantly higher for both smaller and larger particles. This behaviour is quite usual for a mechanical filter and results from the distinct mechanisms by which the filter operates (da Roza, 1982).

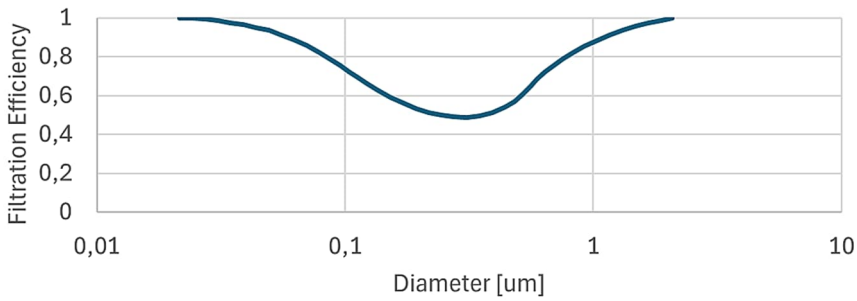

Figure 1. Filtration efficiency of a typical air filter.

4.6.3 Results

Figures 2-4 demonstrate how a particle cloud behaves when interacting with a filter designed to replicate the efficiency of a real-world air filter, as simulated using the application developed in this study. Air flows from left to right in. Figures show how certain particles are trapped by the filter while others pass through.

Additionally, the images demonstrate how the implemented application can calculate the quantity of particulate matter retained within the filters. This information can be utilized to adjust filter efficiency and pressure drop (Berry et al, 2023).

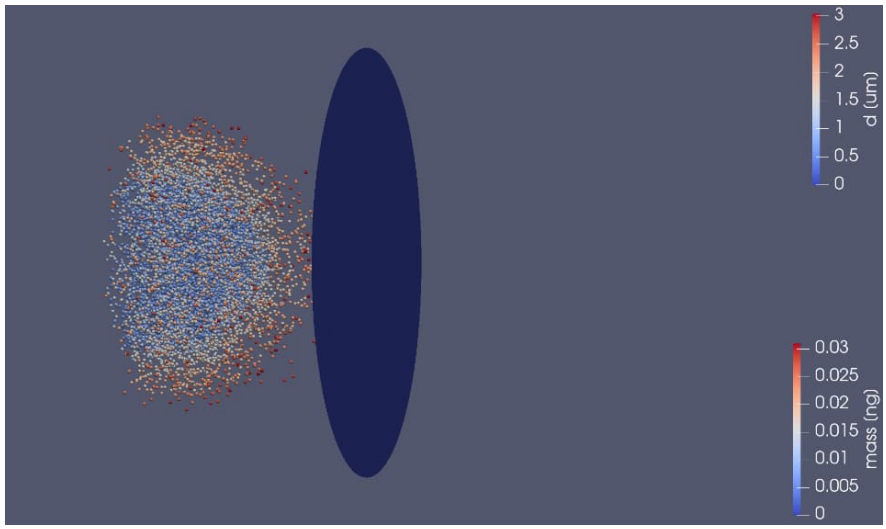

Figure 2. The situation before the particle cloud hits the filter. The flow is from left to right. Diameter *d* refers to the diameter of the particle and *mass* refers to the local mass of the filter (mass per STL patch in filter). It should be noted that the diameter of the particles in the figure is greatly exaggerated.

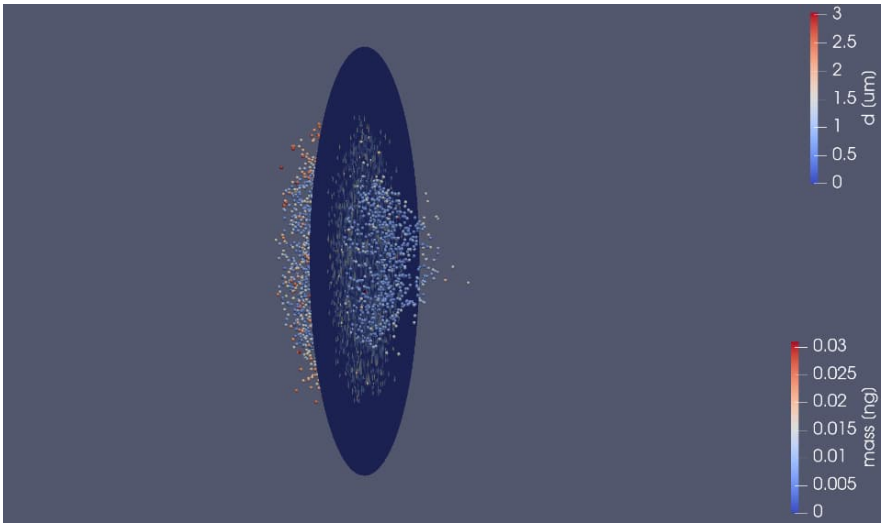

Figure 3. The situation during the particle cloud hits the filter.

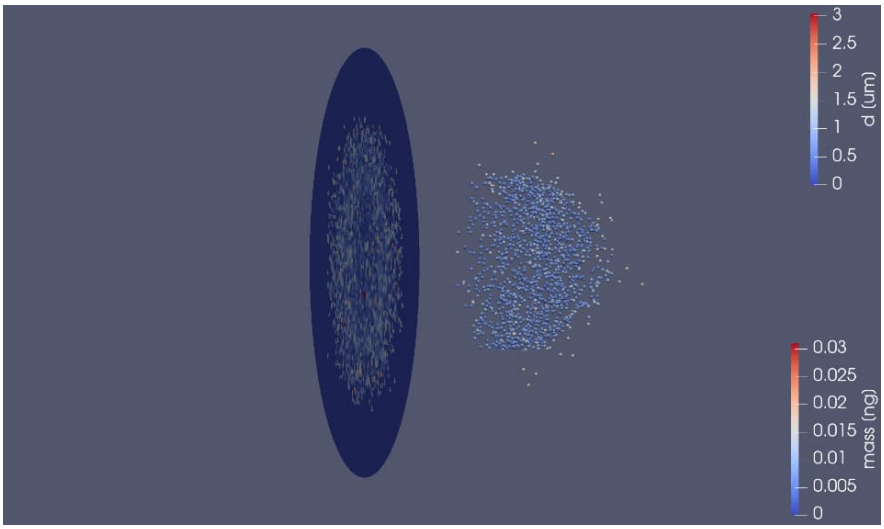

Figure 4. The situation after the particle cloud has hit the filter.

As previously stated, the application can be assigned any filter separation efficiency. This is illustrated in Figure 5, which displays the performance of three distinct filters.

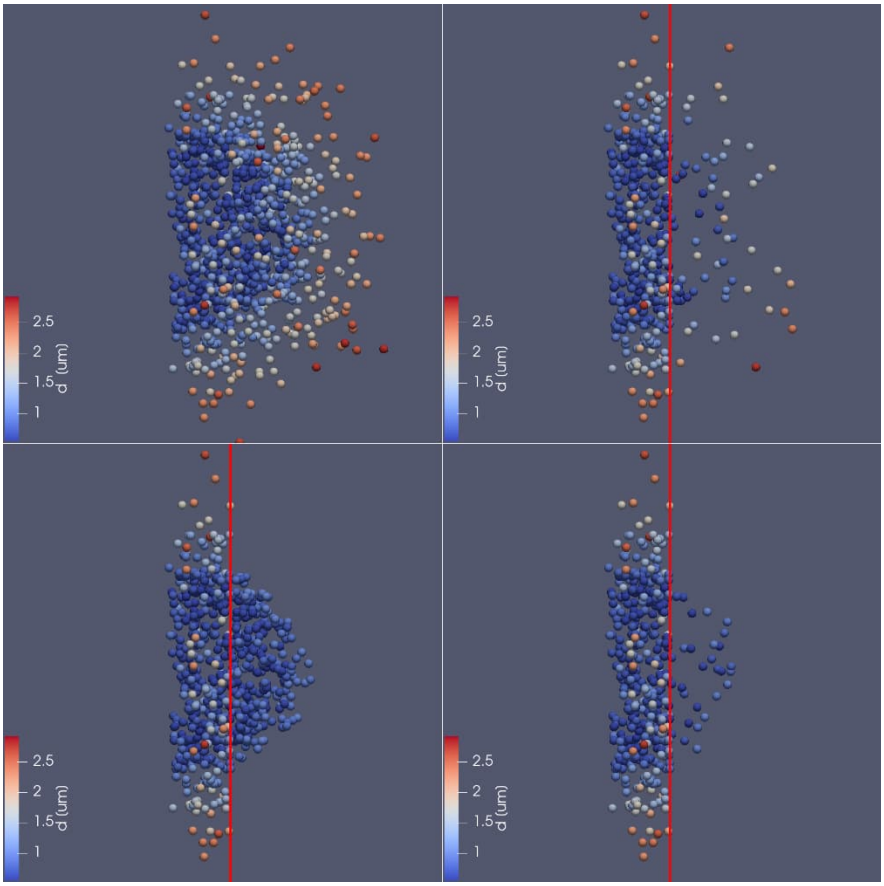

Figure 5. Different filtration scenarios during a particle cloud collision. Top left: without filter. Top right: filter with 90% efficiency across the entire particle size spectrum. Bottom left: filter that is 100% efficient for particles larger than 1 μm but zero efficiency for smaller particles. Bottom right: filter with 100% efficiency for particles larger than 1 μm and 90% efficiency for smaller ones. The filter is marked with a red vertical line.

4.6.4 Conclusions

In this study, an application has been implemented within the most widely utilized open-source CFD software, OpenFOAM, allowing for the integration of an actual air filter (and consequently an air purifier) into the simulation that governs the airflow in a room.

4.6.5 Future study

As it is implemented in this study, the filter's efficiency remains consistent regardless of the material buildup (clogging) within it. Similarly, there is no change in the pressure drop. Incorporating these features will be straightforward and is planned for future projects.

4.6.6 References

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4.7 Microbial disinfection efficacy of Far-UVC radiation in aerosol phase

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Abstract: In this study we explored the disinfection efficacy of 222 nm Far-UVC radiation against different microbes. The radiation was found to be efficient against *Staphylococcus aureus* bacteria, but its efficacy against MS2 virus was only moderate, and against *Bacillus atrophaeus* bacterial spore the efficacy was low.

4.7.1 Background

It is claimed that 222 nm Far-UVC radiation is a type of UV radiation that has a sufficiently effective inactivation effect on microbes at an intensity that is safe for use in the presence of humans. This opens new possibilities for combating airborne pathogens. The effect of enhanced ventilation or an air-circulating air purifier on the particle population in indoor air is typically quite slow: to achieve a 50% reduction, the volume of air in the room must be replaced with clean air. UV radiation, on the other hand, can affect the entire room at once, potentially providing an immediate effect, as seen in the study conducted in a room by Eadie et al. (2022).

The use of Far-UVC in disinfection is new, and most of the research on the disinfection effect of 222 nm Far-UVC radiation in the aerosol phase has been published by groups that report conflicts of interest related to the patenting of the method. For these reasons we decided to verify the disinfection effect of 222 nm radiation through an independent study using three different microbes: the bacterium *Staphylococcus aureus*, the MS2 bacteriophage virus, and *Bacillus atrophaeus* bacterial spores.

4.7.2 Methods

The study was conducted in a cylindrical stainless steel tank with a volume of approximately 2.3 m^3 (Figure 1). A 20 W KrCl excimer lamp was suspended in the center of the tank. HEPA-filtered clean air was introduced into the upper part of the tank at a flow rate of 10 $l\ s^{-1}$, into which microbial aerosol was generated using a nebulizer. A mixing plate was placed in front of the inlet to disperse the jet-like air flow. At the bottom of the tank, a 140 mm diameter fan ensured effective mixing of the tank's contents. Air exited through an opening at the bottom of the tank. The microbial aerosol sample was collected from an opening on the side of the lower part of the tank using an SKC BioSampler into a peptone-saline collection solution.

Experiments were conducted with high (unshielded lamp) and low (shielded lamp) radiation intensity, as well as with low and high dry matter content. In the case of low dry matter content, the microbial solution was diluted by a factor of

1:10 with distilled water, and in the case of high dry matter content, the microbial solution was diluted by a factor of 1:10 with peptone-saline solution. The addition of dry matter content was used to investigate the possible protective effect of internal shading of the particles. *B. atrophaeus* and MS2 virus microbial solutions were mixed and measured simultaneously, while *S. aureus* was measured separately. In each case, four samples were taken with the UV lamp on. The lamp was then turned off, the air was allowed to exchange for 20 minutes, and four control samples were taken. The experiments were conducted at a temperature of 22-24°C and a relative humidity of 31-36%.

The UV radiation intensity was measured with a Gigahertz-Optik X1-5 radiometer equipped with a UV-3727-5 UV sensor. Figure 1 shows the Far-UVC radiation field inside the tank. The radiation field was assumed to be rotationally symmetric, and the results are averages from four rotationally symmetric measurement points.

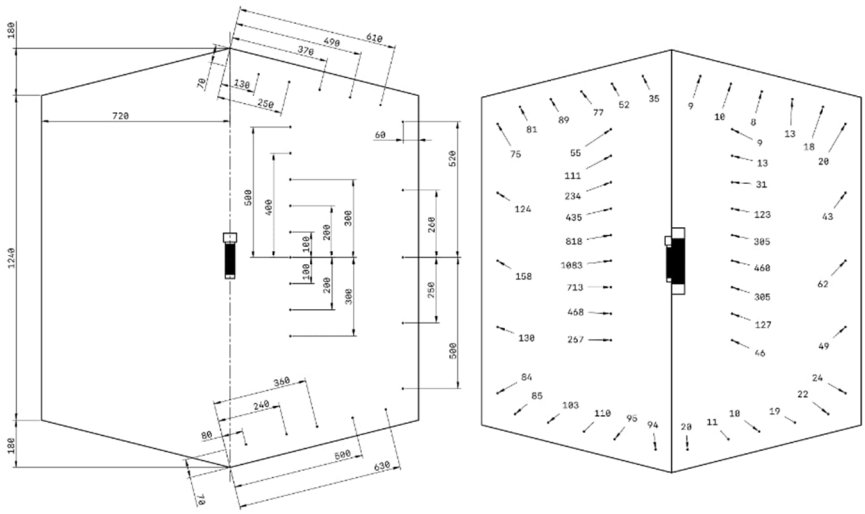

Figure 4. On the left, the dimensions of the measurement chamber in millimeters and the locations of the measurement points. On the right, the UV radiation intensity on the left side in units of μW cm^{-2} without the shield, and on the right side with the shield.

4.7.3 Results

To demonstrate the disinfection efficiency of 222 nm Far-UVC radiation, we required a reduction of over 90% (one logarithmic unit). This was achieved in all experimental setups only with *S. aureus*. For the MS2 virus, we observed over 90% reduction in the case of high intensity and low solid content. Indications of the protective effect of higher dry matter content were observed only in the case of the

MS2 virus. A reduction of more than 30% was observed for all microbes in each experimental setup, and the reduction in high-intensity experiments was greater than in low-intensity experiments in all cases. The results are presented in Tables 1 and 2. A p-value greater than 0.05 indicates that the samples collected with UV light on did not differ in a statistically significant way from the samples collected with UV light off.

It is noteworthy that aerosol production remained consistent. When comparing the corresponding control measurements (UV off) collected during high and low-intensity experiments, the amount of collected microbes remained nearly constant for each microbe. In the case of the MS2 virus, increasing the solid content improved the collection efficiency by approximately two orders of magnitude. This is likely because the MS2 virus itself is smaller than the BioSampler's cutoff, meaning that a higher amount of solid material increases the carrier particles of the MS2 virus, allowing a greater portion of them to be collected by the BioSampler.

Table 1. The decrease of infectious microbes in high-intensity experiments.

	Low dry matter content [%]	P-value low dry matter content	High dry matter content [%]	P-value high dry matter content
S. aureus	99,5±0,2	0,009	99,6±0,4	0,036
MS2-virus	95±6	0,009	83±7	0,007
B. atrophaeus	60±20	0,005	70±8	0,001

Table 2. The decrease of infectious microbes in low-intensity experiments.

	Low dry matter content [%]	P-value low dry matter content	High dry matter content [%]	P-value high dry matter content
S. aureus	93,0±1,4	0,002	94±2	0,002
MS2-virus	50±30	0,052	30±30	0,09
B. atrophaeus	40±20	0,016	40±20	0,0006

4.7.4 Discussion and conclusions

The results are in line with the study published by Eadie et al. (2022). In the low-intensity case, the radiation intensity is about four times higher than in the experimental setup by Eadie et al. (2022), and the residence time was about one-fifth. Eadie et al. (2022) observed a reduction of approximately 98% for *S. aureus*, while in this study, a reduction of 93% was achieved.

Influenza and coronaviruses are enveloped and are less resistant to UV radiation than *S. aureus*. The MS2 virus is non-enveloped and proved to be more resilient than *S. aureus*. Bacterial spores are typically very resistant, and no significant disinfection effect was achieved for *B. atrophaeus* in this study.

In conclusion, the use of 222 nm Far-UVC radiation for the inactivation of airborne microbes appears to be a promising method, especially for relatively sensitive microbes such as coronaviruses, influenza viruses, and *S. aureus*. However, stronger evidence is still required regarding the health safety of the far-UVC radiation, and there is not yet sufficient research data on the potential harmful effects of continuous long-term exposure. Since the disinfection effect on some microbes is almost immediate, a safe use case in the presence of people might be one where the UV lamps are not constantly on, but rather used as needed for a few minutes or tens of minutes at a time.

4.7.5 References

Eadie, E et al. (2022). Far-UVC (222 nm) efficiently inactivates an airborne pathogen in a room-sized chamber. *Scientific Reports* 12(1), 4373

4.8 Enhanced Microbial Inactivation Using Far-UVC: Insights from CFD simulations

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EXTENDED ABSTRACT

4.8.1 Background

In recent years, Far-UVC irradiation has gained attention for its potential to inactivate microbial populations without posing significant risks to human health. Far-UVC, particularly within the wavelength range of 200–230 nm, offers a germicidal effect without penetrating the skin or eyes, making it an appealing disinfection tool for various environments such as healthcare facilities, public spaces, and transportation systems. Previous research has demonstrated the effectiveness of Far-UVC radiation against airborne viruses and bacteria, but further studies are needed to understand its performance in specific configurations, such as cylindrical chambers with variable airflow and UV transmittance properties. This study focuses on assessing the microbial inactivation efficacy of Far-UVC within a controlled cylindrical chamber, with particular attention to parameters like UV lamp efficiency, transmittance, and airflow dynamics.

This study aims to provide a comprehensive understanding of how these factors influence microbial inactivation. The results of present research could have significant implications for the design and implementation of UV-based disinfection systems, particularly in environments that require continuous microbial control, such as hospitals, laboratories, and public transportation.

4.8.2 Methods

This study utilized computational fluid dynamics (CFD) to simulate the behaviour of Far-UVC radiation and its interaction with microbial particles within a cylindrical chamber. The chamber was equipped with a Kr-Cl excimer Far-UVC lamp, and airflow was managed using a fan and diffusion cone to ensure uniform exposure, as depicted in Fig. 1. The discrete ordinates model was applied to simulate the UV irradiation, while the discrete phase model and discrete random walk were used to track microbial movement and interaction with the irradiated air. Nine different cases were simulated with varying Reynolds numbers, UV transmittance (UVT) values, and UV lamp efficiencies to explore the influence of these parameters on disinfection effectiveness, as shown in Table 1. To calculate the UV dose received by microbes, a user-defined function (UDF) was developed. The UV dose, measured is a function of the logarithmic reduction of microbial populations.

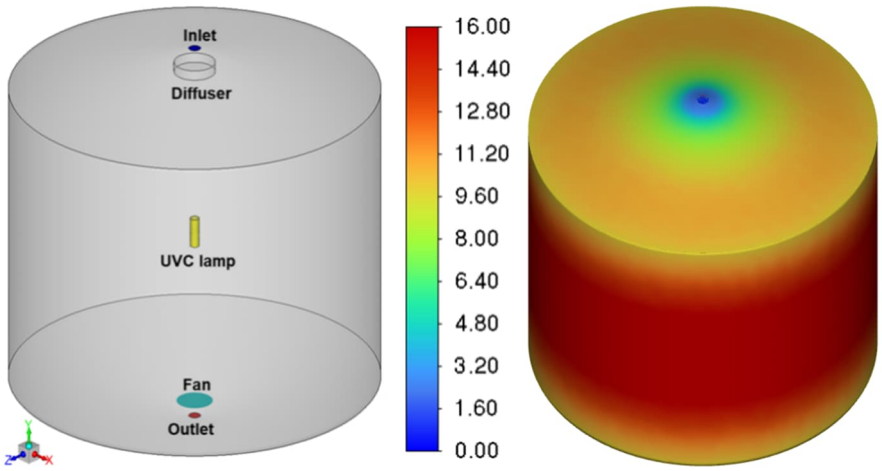

Figure 5 Schematic diagram of cylindrical chamber and irradiance distribution for case 2.

Table 1 Case study illustrating input parameters and respective REDs.

	Re	**UVT (%)**	**UVC efficiency**	**Diffuse irradiation (W/m^2)**	**RED**
Case 1	4.38×10^5	90	40	600	0.024542
Case 2	6.57×10^5	100	100	1500	29.846249
Case 3	8.76×10^5	90	40	600	0.040785
Case 4	6.57×10^5	100	70	1050	27.098875
Case 5	6.57×10^5	100	40	600	21.992313
Case 6	6.57×10^5	90	40	600	0.010159
Case 7	6.57×10^5	80	40	600	0.003834
Case 8	6.57×10^5	70	40	600	0.000149
Case 9	6.57×10^5	60	40	600	0.000027

Microbial inactivation was quantified using a reduction equivalent dose (RED) based on dose-response relationships. RED is calculated by integrating the

irradiance over the path and time of exposure for each microbial particle as it moves through the chamber.

4.8.3 Results

The CFD model was validated by comparing the numerically predicted fluence rates with previously published experimental data. The results showed a high degree of agreement, with a maximum deviation of approximately 2%, indicating that the numerical model is well calibrated and capable of accurately predicting the distribution of UV irradiance within the chamber.

The flow dynamics within the chamber were highly dependent on the inlet velocity and the design of the diffuser. At lower Reynolds numbers (*Re* = 4.38×10^5), the flow exhibited significant buoyancy-driven behaviour, with a downward jet forming near the fan. As *Re* increased to 6.57×10^5 and 8.76×10^5, the flow became more turbulent, with higher kinetic energy and more efficient mixing.

The UV irradiance was highest near the lamp, with a steep decline as the distance from the lamp increased, as manifested in Fig. 1. The distribution of UV light was influenced by the efficiency of the UV lamp, with higher efficiencies resulting in higher overall irradiance. In cases where the UV lamp efficiency was reduced to 40%, the UV light was more evenly distributed but at a lower intensity, suggesting that longer exposure times would be required to achieve effective microbial inactivation.

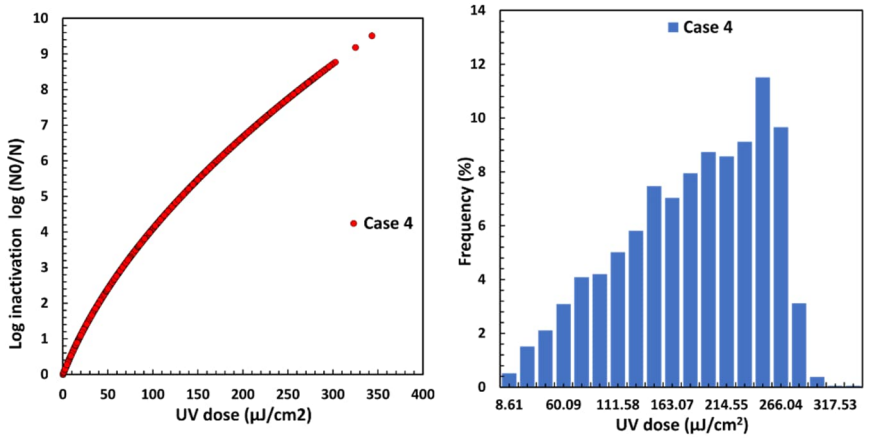

Figure 6 UV dose response curve and Frequency (%) vs UV dose distribution histogram for Case 4.

The study revealed significant variability in UV dose distribution and microbial inactivation rates across the different cases. Higher UV doses were associated with increased microbial inactivation, although a plateau effect was observed

beyond certain doses, indicating a diminishing return on microbial reduction, as depicted in Fig. 2. Additionally, Fig. 2 shows that cases with higher UV lamp efficiency and greater airflow exhibited more uniform UV dose distributions, leading to more effective disinfection. In contrast, cases with low UVT or low lamp efficiency showed narrow, low-dose distributions, where microbial inactivation was insufficient. The optimal conditions for disinfection were found in scenarios with a combination of high UV lamp efficiency and moderate to high airflow.

4.8.4 Discussion and conclusions

The present results highlight the critical role of UV lamp efficiency and airflow dynamics in ensuring effective microbial inactivation within UV irradiation systems. While higher UV doses generally led to increased microbial inactivation, the plateau effect suggests that the most susceptible microbes are inactivated early in the process, with diminishing returns for higher doses. Additionally, the study underscores the importance of optimizing UV lamp placement and airflow management to achieve a uniform UV dose distribution, especially in confined environments like cylindrical chambers. This study provides valuable insights into the effectiveness of Far-UVC radiation for microbial inactivation in cylindrical chambers, demonstrating the importance of UV lamp efficiency, airflow, and UV transmittance in achieving optimal disinfection. Scenarios with high UV lamp efficiency and appropriate airflow yielded the best results, while low-efficiency lamps or poor airflow resulted in suboptimal microbial inactivation. These findings suggest that careful system design and parameter optimization are essential for maximizing the efficacy of Far-UVC disinfection systems, particularly in environments requiring continuous microbial control, such as hospitals and public spaces.

These findings can guide the design of more efficient UV-based disinfection systems for real-world applications, such as hospital air disinfection and surface sterilization in public transportation systems.

5 Calculation and controlling of transmission risks

5.1 Transmission risk and control strategies for respiratory infections in buildings

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Abstract: Pathogen transmission risk in indoor environments rises during pandemics. Respiratory viruses spread via direct contact, fomites, droplets, and aerosols, requiring comprehensive nonpharmaceutical interventions. The study highlights the high risk of SARS-CoV-2 transmission in indoor settings, like households, schools, hospitals and particularly at singing events and fitness centres. COVID-19 is recognized as an occupational disease, especially among health professionals and personal care workers in Finland. Effective prevention includes hygiene, ventilation, and personal protective equipment. Risk assessment models for airborne long-range transmission and a generic risk banding model for occupational exposure to all kinds of biological agents were developed.

5.1.1 Transmission risk in different indoor settings

The risk of pathogen transmission in indoor environments is increased during pandemics and epidemics. According to WHO, over 775 million coronavirus disease 2019 (COVID-19) cases have been diagnosed worldwide until August 2024. Important venues for SARS-CoV-2 transmission have been households (secondary attack rate SAR up to 37.3%; 95% CI:32.7–42.1%) but large infection clusters have been reported also e.g. in schools, hospitals, elderly care facilities, public transportation, and social settings (Madewell et al., 2022, Thompson et al.,

2021). From the mitigation point of view, it is important to understand which settings and behaviours are associated with increased risk of transmission. Therefore, Francis et al. (2024) studied the risk of SARS-CoV-2 transmission in a community indoor setting and found that transmission was highest in the following indoor settings: singing events (SAR 44.9%) and fitness centres (SAR 28.9%) (Francis et al., 2024).

5.1.2 Occupational diseases

Respiratory diseases are the most common reason for short sickness absence (1-10 days) in working life[1]. Of these, only about a fifth are diagnosed, i.e. the cause of the disease is usually not determined. Very few cases of respiratory infections end as occupational diseases because they require a diagnosed disease. An occupational disease is a disease that is likely and mainly caused by a biological agent at work, in the area where the work is performed, during work-related training or travelling.

Since the outbreak of the coronavirus pandemic, the recognition of COVID-19 infections as an occupational disease has been most common among health associate professionals and personal care workers in Finland (Koskela et al., 2024). After the healthcare sector, more recognized cases of occupational diseases have occurred in education, service, transport and social care occupations. Several confirmed cases of occupational diseases are particularly prevalent in the following occupational groups, such as nurses, midwives, practical nurses, childminders, and kindergarten teachers. Some clusters of COVID-19 infections have also occurred in industry (e.g. food and shipbuilding) and on construction sites.

5.1.3 SARS-CoV-2 coronavirus infections among daycare staff

Due to the high rates of sickness absence of childminders and kindergarten teachers (e.g. 21.49-32.65 sick days per person-years-worked during the years 2020-2022), we investigated the proportion of SARS-CoV-2 coronavirus infections among daycare staff. IgG antibodies against two different SARS-CoV-2 antigens, the viral spike glycoprotein (S-antigen) and the internal nucleocapsid protein (N-antigen), were measured in blood samples taken from daycare workers. 37 employees participated in the study in 2023 and 33 employees in 2024, and the sera of their blood samples were analysed for S-IgG and N-IgG antibodies at HUS's Diagnostic Center.

Overall, 100 % of the samples from daycare workers studied were seropositive based on S-antigen antibodies in both years. S-IgG antibodies are formed as a result of both coronavirus infection and the COVID-19 vaccine. 96% of the participants in the study had taken at least one coronavirus vaccine in 2021–2022.

[1] Work-life knowledge service | www.worklifedata.fi (tyoelamatieto.fi

Daycare workers still had high S-IgG coronavirus antibodies in April 2024, even though only 12% of them had received the COVID-19 vaccine in the year before sampling. Thus, especially in 2024, S-IgG coronavirus antibodies have probably been formed from new SARS-CoV-2 virus infections. Re-infection easily raises antibody levels thanks to the body's memory cells and maintains antibodies, especially to the S-antigen.

International studies have shown that a very large proportion have measurable amounts of IgG antibodies at least six months after the coronavirus infection or vaccination, but especially the N-IgG antibody levels wane after that. N-IgG antibodies caused by the coronavirus infection are only formed as a result of the infection, because the nucleoprotein is a part of the virus that is not included in the current coronavirus vaccines. Of the kindergarten workers examined, 32% had IgG antibodies to the N-antigen in 2023 and 48% in 2024.

Similarly, a Norwegian study (Tunheim et al., 2024) found that N-seropositivity in the vaccinated adult population is low and cannot be used to estimate the extent of SARS-CoV-2 infections because new and antigenically different coronavirus variants are constantly emerging. Low N-IgG antibody levels can be caused by the so-called immune imprinting, whereby the body's immune system develops the strongest antibodies in repeated exposure to the S-antigen that it has encountered in a previous viral infection or vaccination.

Based on our results, it can be concluded that the staff of Finnish daycare centers have had several exposures to the coronavirus, so one significant reason for sickness absences has been the COVID-19 infections.

5.1.4 Four modes of transmission

Respiratory viruses spread through four primary methods: direct physical contact, indirect contact via surfaces (fomites), large droplets, and fine aerosols. In a 2009 study, Nicas and Jones analysed how these pathways contribute to the risk of influenza infection (Nicas and Jones, 2009). They discovered that the likelihood of a virus infecting the lower versus upper respiratory tract, along with the concentration of the virus in saliva, influences the significance of each transmission route. Their findings suggest that the importance of each pathway varies depending on specific circumstances, which are often unpredictable. Azimi et al (2021) studied the relative importance of the transmission routes of SARS-CoV-2 in the famous Diamond Princes cruise ship outbreak. They estimated that before the passenger quarantine the contribution of long-range, fomite and short-range transmission were 42%, 37% and 22%, respectively. Consequently, interventions during a pandemic must address all potential exposure routes, including inhalation, hand contact, and droplet spray (Nicas and Jones, 2009).

The importance of the inhalation transmission route has been overlooked in earlier evaluations (Morawska et al., 2023). However, it has been recognized that inadequate ventilation contributes to the spread of diseases such as measles, tuberculosis, rhinovirus, influenza, and SARS-CoV-1 (Allen and Ibrahim, 2021).

Several factors affect the spread of pathogen-containing aerosols and thereby the risk of contagion. La Torre et l. identified several key factors affecting the risk of SARS-CoV-2 infection among healthcare workers (La Torre et al., 2021). They found that longer contact time, especially over 15 minutes, significantly increases the risk of infection. Similarly, contact distance plays a crucial role. Being close to an infected person (within 1 meter) is a major risk for transmission. Since SARS-CoV-2 is transmitted through respiratory aerosols, which can stay aloft for extended periods and travel beyond 6 feet, increasing outdoor air ventilation can significantly reduce the concentration of airborne viruses indoors (Allen and Ibrahim, 2021).

5.1.5 Estimating the risk of transmission

Evaluating the risk of airborne infection transmission starts with identifying what is released into indoor air (Kulmala et al., 2024). This step is the most uncertain because the number of pathogens emitted can vary significantly. This variation is due to the differing rates at which individuals emit respiratory particles and the viral load they carry.

The Wells–Riley model is widely utilized for assessing the risk of respiratory infectious diseases in indoor environments. The model offers a quick assessment method. It relies on a theoretical unit called the quantum of infection, which represents the number of infectious airborne particles needed to cause infection in a person. This quantum can consist of one or more particles (Sze To and Chao, 2010).

Several studies suggest employing dose-response models to evaluate infection risk. These models necessitate data on the infectious dose to establish the dose-response relationship (Sze To and Chao, 2010). Unlike the Wells–Riley model, which focuses solely on airborne transmission, dose-response models can consider multiple transmission routes. They also measure the infectious source strength of an outbreak by the actual quantity of the pathogen, rather than using a theoretical unit (Sze To and Chao, 2010).

However, current methods based on fixed contaminant generation rates may not adequately capture the complexity of infection transmission. Models using the quantum concept often assume at least one infectious person is present in a room, which may not always be true, especially with fewer occupants. This can lead to overestimated infection risks. Therefore, a more realistic model is needed to consider disease prevalence and varying pathogen emission rates. Kulmala et al. developed a straightforward yet scientifically robust model for airborne pathogen transmission, applying it to real-life scenarios in a daycare centre (Kulmala et al., 2024). This model was also used to estimate the impact of air cleaners on reducing the number of people at risk of SARS-CoV-2 transmission (Vartiainen et al., 2024)

In addition to human-to-human disease transmission, other biological hazards occur in many different workplaces. Such agents include zoonotic or environmental bacteria, fungi (yeasts and moulds), viruses, protozoa, parasites,

and prions. Biological hazards are most found in agriculture and forestry, energy production, waste and environmental management, and social and health care. Exposure can occur through the respiratory tract as aerosol and droplet infection, contact infection of the conjunctiva, skin or mucous membrane, ingestion into the digestive tract, animal bite or insect sting.

Biological agents cause a lot of health hazards every year. Most commonly, they cause infectious diseases, but also other diseases, such as allergic alveolitis and asthma. To assess workers' exposure, the employer shall determine the probability, nature, amount, and duration of the exposure, as well as the severity of the possible harm. Based on these, the magnitude of the risk to the health or safety of the worker can be assessed and the necessary measures to prevent and reduce possible exposure can be decided. This has proven to be a challenging task for employers. Therefore, Laitinen et al 2024 developed a generic tool for assessing the risks of biological agents in occupational settings.

5.1.6 Means to reduce contagion risk

A rational approach to reducing the risk of contagion without pharmaceuticals involves minimizing exposure transmission routes. The key question is identifying the dominant pathways of exposure. These pathways vary depending on the disease and the situation, making a straightforward answer difficult. For instance, theoretical studies indicate that for influenza, the significance of different transmission modes changes with the viral load in expelled respiratory fluids. When the viral load is high, airborne transmission becomes more critical than droplet transmission (Nicas and Jones, 2009). Therefore, a mix of control measures is essential for disease prevention, especially when the characteristics of a new disease are unknown.

Several institutions have issued guidelines for infection prevention and control.[2,3,4,5] Standard precautions include staying home when sick, conducting risk assessments for premises and activities, maintaining good hand hygiene, practising respiratory hygiene and cough etiquette, and using personal protective equipment. Additionally, environmental cleaning, sanitation, decontamination, and effective communication are crucial.

One of the most effective ways to reduce contagion risk is to focus on lowering pathogen emissions. This can be achieved by following proper coughing and sneezing etiquette and using masks and other personal protective equipment.

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[2] https://iris.who.int/bitstream/handle/10665/375200/WHO-2019-nCoV-IPC-guideline-2023.4-eng.pdf?sequence=1

[3] https://thl.fi/en/topics/infectious-diseases-and-vaccinations/diseases-and-disease-control/preventing-respiratory-tract-infections

[4] https://www.ttl.fi/teemat/tyoterveys/pandemiat-ja-epidemiat/koronaohjeita-tyopaikoille-ja-tyoterveyshuolloille

[5] https://www.ecdc.europa.eu/en/covid-19

Moreover, the rate of respiratory droplet emission increases with the loudness of speaking or singing, thereby increasing pathogen emissions. However, these measures heavily rely on people's behaviour. Thus, the evidence of the masks and respirators has been contradictory. Therefore, Mäkelä et al (2024) conducted a literature review on mask effectiveness studies and their results (Mäkelä et al., 2024). They found that cloth masks provide some protection, but surgical masks perform better. Respirators with higher filtration efficiencies and better fit (e.g. FFP2 and FFP3) offer superior protection.

Increased dilution more rapidly reduces particle concentration in indoor air, thereby reducing the intensity of exposure and duration that airborne aerosols stay inside a room. This can be realised through outdoor air ventilation or by combining outdoor ventilation with portable air cleaners. Present guidelines for ventilation rates take into account both the number of people and the size of the room. For instance, in classrooms and offices, the existing Category I ventilation is generally sufficient during pandemics. However, spaces like meeting rooms, restaurants, and gyms require increased ventilation to ensure safety (Kurnitski et al., 2023, ASHRAE, 2023). Implementing these changes involves costs and design adjustments, but benefits include reduced disease transmission and improved indoor air quality (Allen and Ibrahim, 2021). Säämänen et al (Säämänen et al., 2024b, Säämänen et al., 2024a) studied the influence of the use of air cleaners on the energy cost as well as compared the energy efficiency of the different cleaning technologies. It was found that the energy costs of the air cleaners were only 20-25 % of what they would have been if the general ventilation rate would have been increased as much as the clean air delivery rates of the air cleaners were.

Facility management and interventions in building operations have a key role in indoor infection control. Facility management interventions could focus on hard services such as HVAC and drainage systems, soft services like cleaning and disinfection and space management including space planning and occupancy controls (Zhang et al., 2022).

The following Table 2 summarises the mitigation and control measures that can help reduce respiratory infection transmission in indoor settings. These measures are classified depending on whether they focus on the infectious person, transmission pathway or the susceptible person who is exposed to the viral pathogens.

Table 2. Transmission mitigation and control measures for different exposure routes and different parts of pathogen path from index (source) to susceptible (receiver) in indoor settings.

Transmission route	Mitigation and control measures		
	Source	Dispersion	Receiver
Airborne	FFP2 masks Reducing voice use Avoiding heavy physical exercise	Enhanced ventilation Air cleaners UV irradiation RH control	FFP2 masks Avoiding crowds Reducing time spent in mass gatherings Avoiding physical exercise that causes increased breathing rate
Droplet	Surgical masks Reducing voice use Coughing and sneezing etiquette	Physical barriers Physical distancing	Surgical masks or FFP2 masks Eye protection
Contact	Surgical masks Coughing and sneezing etiquette	Disinfection of frequently touched surfaces Contactless operations	Hand hygiene Avoidance of face touching Avoidance of shaking hands

5.1.7 Different airborne pathogen control technologies

Several studies have been performed to study the efficiency of the various air filters against several microbes. Air filters used in residential HVAC systems is effective at capturing airborne virus particles and the viral filtration efficiency is correlated to its filtration efficiency rating in general (Zhang et al., 2020). The coarse air filters usually installed e.g. in recirculation systems have been judged inefficient in removing infectious particles from air (ASHRAE 241-2023). Higher-rated filters have a better ability to retain pathogens. HEPA and better-rated filters have been shown to have filtration efficiencies better than 99.99% for several pathogens (Harstad et al., 1967) (Roelants et al., 1968) (Zacharias et al., 2021) (Saccani et al., 2022). However, it has been shown that air filter grade corresponding to F8 has viral filtration efficiency of over 95% (Zhang et al., 2020) (Saccani et al., 2022).

Air cleaners with fibrous and electrostatic filters are effective, but electret filters can degrade over time. High-efficiency filters may reduce clean air delivery rate due to increased pressure drop (Schumacher et al., 2022).

UVC light (with wavelengths between 200 and 280 nanometers) is effective in inactivating microorganisms by damaging their DNA or RNA, preventing them from

replicating. UVC disinfection can be used in indoor environments by installing UVC lights in air ducts of HVAC systems or used as standalone units in rooms. The UVC efficiency depends on the dose the microbe gets and especially the type of the microbe. For easy-to-kill viruses their energy consumption is comparable to that of air cleaners (Säämänen et al. 2024a) Direct exposure to UVC light can be harmful to skin and eyes, so proper safety measures must be implemented when using UVC disinfection systems. UV lights can inactivate harmful pathogens, but they do not remove them from the air. Far-UVC at 222 nm is considered non-harmful to human health and effective for disinfection purposes, making it safe for occupied spaces. Far-UVC allows for whole-room direct exposure of occupied spaces, potentially offering greater efficacy, while evidence supports its use within existing safety guidelines.

5.1.8 References

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5.2 The Risk of SARS-CoV-2 Transmission in Community Indoor Settings: A Systematic Review and Meta-analysis

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EXTENDED ABSTRACT

5.2.1 Background

There is considerable evidence that in indoor settings severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) spreads primarily by short- and long-distance airborne transmission through respiratory aerosols (Duval et al., 2022). A recent systematic review reported the potential for long-distance airborne transmission in community indoor settings like restaurants, workplaces, and choir venues (Duval et al., 2022). Within indoor settings, environmental factors such as ventilation, preventive measures (including mask-wearing, hand hygiene, and social distancing), and contact patterns (the proximity of occupants, exposure duration, and type of activity) can play an important role in SARS-CoV-2 transmission, in addition to host and viral factors (Meyerowitz et al., 2021). Updated evidence on the risk of transmission and its modifying factors in various community indoor settings can help develop new prevention and control measures.

Although vaccines are the most effective preventive measures for severe illness, they do not substantially reduce SARS-CoV-2 transmission in crowded settings and against newer variants (Marcelin et al., 2022). Our study, therefore, focused on the added benefit of accounting for different setting types and characteristics to improve the interpandemic prevention of SARS-CoV-2 and other respiratory pathogens. We conducted a systematic review and meta-analysis to estimate the secondary attack rate (the percentage of contacts of an index case that tested positive for SARS-CoV-2) of SARS-CoV-2, including the factors modifying the risk of transmission in community indoor settings.

5.2.2 Methods

We searched electronic databases (Medline, Scopus, Web of Science, WHO COVID-19 research database) and preprint servers (MedrXiv and BiorXiv) using a systematic search strategy from 1 January 2020 to 20 February 2023. We included articles with original data for estimating the secondary attack rate (SAR) of SARS-CoV-2 in community indoor settings such as workplaces, restaurants, bars, nightclubs, shopping and fitness centers, religious gatherings, and sporting

and singing events. We deduplicated the citations aggregated from the electronic databases, and two investigators (MRF and SG) screened the studies according to the eligibility criteria. We also extracted data and assessed the epidemiological quality of all eligible studies in duplicate using pre-piloted questionnaires. Using these data, we estimated the overall and setting-specific SARs using the inverse variance method for random-effects meta-analyses. We also performed subgroup analyses to investigate the index, viral, setting and study-level factors potentially modifying the SARs in the included settings.

5.2.3 Results

We screened a total of 7866 studies, and 34 eligible studies containing data on 45 transmission events were included in our review. All the studies found were conducted between January 2020 and December 2021, when the dominant SARS-CoV-2 variants were Wuhan wild type (n = 30 studies), Delta (n = 2), and Omicron (n = 2). Most studies were conducted in China (n = 8), the United States (n = 5), and South Korea (n = 5). The included studies contained information on 577 index cases, 898 secondary cases, and 9173 contacts (Francis et al., 2024).

The pooled SAR for community indoor settings was 20.4% (95% confidence interval [CI], 12.0%–32.5%). The setting-specific SARs were highest for singing events (SAR, 44.9%; 95% CI, 14.5%–79.7%), indoor meetings and entertainment venues (SAR, 31.9%; 95% CI, 10.4%–65.3%), and fitness centers (SAR, 28.9%; 95% CI, 9.9%–60.1%). The setting-specific SAR was the lowest for workplaces (SAR, 6.2%; 95% CI, 2.5%–14.4%). There was significant between-study heterogeneity observed when estimating the setting-specific SARs (85.8% - 97.3%). We did not find any statistically significant difference in SARs by index case, viral, and setting-specific characteristics (Francis et al., 2024).

5.2.4 Discussion and conclusions

Our systematic review provides evidence on the community indoor settings that have the highest risk of SARS-CoV-2 transmission. Highest SARs were observed for singing events, community settings like indoor meetings and entertainment venues, and fitness centers. Rates were lowest for workplaces. We found no significant differences in SARs by index case, viral, and setting-specific characteristics, possibly because of small sample size and varying definitions.

The exceptionally high SAR for singing events suggests that long-distance airborne transmission may have occurred in at least some events (Duval et al., 2022). Singing in poorly ventilated and overcrowded indoor spaces is known to facilitate SARS-CoV-2 transmission. When considering risk mitigation in these settings, it is important to continue highlighting the risks of singing and loud vocalization, particularly in poorly ventilated spaces.

The risk of secondary transmission was relatively high in fitness centers, possibly due to the increased aerosol emission during high-intensity exercise. Not wearing masks, extended close contact, and poor facility ventilation may also have facilitated transmission in these settings (Francis et al., 2024). Implementing universal mask wearing, reduced occupancy, and improved facility ventilation may reduce the risk of transmission in fitness centers (Li et al., 2021).

The low risk of secondary transmission in workplaces could be due to timely and effective control measures such as regularly testing employees, universal masking, social distancing, paid sick leave, and remote working. More research is needed to better understand the impact of workplace policies on reducing SARS-CoV-2 transmission risks in workplaces.

In conclusion, although vaccination is the cornerstone of COVID-19 prevention, our study provides evidence on the added benefit of accounting for setting types and characteristics to strengthen prevention efforts for respiratory pathogens. We recommend tailored mitigation measures shown to be effective in high-risk indoor settings, such as assessing and improving ventilation.

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5.3 Airborne SARS-CoV-2 transmission in a daycare centre

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EXTENDED ABSTRACT

5.3.1 Background

Infectious respiratory diseases are usually spread through direct contact, droplet, or aerosol transmission. The relative importance of each mode varies depending on the disease and it is often difficult to determine precisely. A case in point is severe acute respiratory coronavirus (SARS-CoV-2), which was initially believed to spread mainly through contact or droplets, but which is now increasingly recognized as also being transmitted by airborne route. Consequently, there has been increasing interest in modelling the airborne dispersal of SARS-CoV-2 and the airborne transmission risk to help assess the effectiveness of various control measures.

When infected individuals sneeze, cough, sing, talk or even breathe, they emit particles over a wide size range, from submicron aerosols to droplets over 1 mm in size (Kulmala et al., 2024). These particles may contain pathogens, the number of which depends on the pathogen concentration in the respiratory fluid and the volume of the droplet. Small droplets measuring < 15 µm evaporate in fractions of seconds, leaving residual aerosol particles that can remain airborne for hours and if inhaled, can penetrate deep into the lungs. Larger droplets with a diameter of >100 µm evaporate too but at a much slower rate than the small droplets. The large droplets behave like ballistic projectiles and settle rapidly close to the point of emission. They are not inhalable but can cause droplet transmission risk when droplet spray lands on the facial mucous membranes of a susceptible person within close range. Aerosols of intermediate size – up to 100 µm – can be inhaled but are trapped in the upper respiratory tract.

The assessment of the airborne infection transmission risk begins with the determination of emissions into indoor air. This is also the source of the greatest uncertainty because pathogen emissions vary hugely. This is because emission rates of respiratory particles and their viral load differ greatly between individuals. Therefore, the current quanta based methods assuming fixed contaminant generation rates may be inadequate to describe the complex phenomena. Moreover, models using quanta concept usually assume that there is at least one infectious person in a room, which may not be the case, especially when there are

only relatively few occupants at the same time. This leads to unrealistically high infection transmission risks. Therefore, a more realistic model is needed to take into account the prevalence of the disease as well as the different pathogen emission rates in the infection transmission risk models.

5.3.2 Methods

When calculating the respiratory emission rate of <5 micrometer particles which can penetrate deep in the lungs and mainly contribute to airborne transmission, it is important to note that the diameter of the dried droplets is about a third of the original. Using this information, the emission rates of respiratory droplets can be estimated at the mouth level. In the literature, the measured droplet emission rates are often reported for the dried particles and to convert these results to the mouth exit conditions the reported mass emission rates need to be multiplied by around 30. Combining the droplet emission rate at mouth exit q (ng/s) with the viral load of the respiratory fluids c_V (RNA copies/mL) the pathogen emission rate G (RNA copies/s) from an infectious person can be estimated as

$$G = q\, c_v \cdot 10^{-9}$$

where the multiplier 10^{-9} comes from the conversion of ng to g assuming a density of 1 g/mL for the expelled droplets.

The dried droplet nuclei are transported, dispersed, and transformed to yield concentrations that vary in time and space. The resulting airborne pathogen concentration C_S (RNA copies/m^3) in a steady-state situation can be estimated by taking into consideration the factors that reduce the pathogen concentrations in the air. These include removal by ventilation, inactivation, deposition and effects of possible air cleaners.

Breathing air containing pathogens causes a dose whose magnitude affects the risk of illness. This was assessed using respiratory rate and infectious doses for SARs-CoV-2 found in the literature.

In the work, the airborne infection transmission risk was calculated hourly in a daycare centre for each room taking into consideration the activities that affect the emission. In addition to average values the effect of parameter variations was studied with Monte Carlo simulations using known log-prob distribution for viral concentrations and uniformly distributed values for other parameters.

The model was validated in a long-term intervention study where room air cleaners were installed two day-care centres and their effect on sick leaves was examined by questionnaires (Vartiainen et al., 2024).

5.3.3 Results

There were large variations in the calculated probability of SARS-CoV-2 transmission between the rooms. The highest probability (3.3%) was more than

100 times higher than the lowest one (0.03%). The lowest probability is in the rooms characterised with high ventilation rates, a small number of persons and low-level activities. In some rooms the calculated generation rate of pathogens was low because of the small number of people in the room: the probability that an index person is in the room is directly proportional to the number of people in the room. The highest calculated risk was in the most occupied location, namely in the changing rooms and in the rooms where lunch was served.

The intervention study revealed that the sick leaves in the day-care centre with air cleaners were 32 % lower than without them (Vartiainen et al., 2024). The predicted expected number of persons at infection transmission risk was somewhat greater, 53 and 60 %, but taken into consideration that the predictions do not consider other exposure locations the results are convincing.

5.3.4 Discussion and conclusions

The relatively simple but scientifically sound model for transmission of airborne infectious pathogens enables the evaluation of pathogen emissions from an infectious person, which is a key factor in the calculation of air concentrations and inhalation doses. Although there can be very large variations and uncertainties in these parameters, the model nevertheless facilitates the assessment of the risk of infection with different parameter values. In addition, the relative effect of various control measures can be determined quantitatively. Ranking of high-risk rooms and activities enables an efficient focus on the risk mitigation measures.

The model was validated in a long-term intervention study where the effect of additional air cleaners on sick-leaves was investigated. Although there were some differences, the reported reductions in infections were in line with predictions. This improved understanding will be useful in evaluating the efficiency and cost effectivity of various control measures.

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5.4 A semi-quantitative risk assessment and management tool for biological agents for workplaces

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Abstract: Occupational risk assessment aims to ensure safe, healthy and smooth working. We have developed a semi-quantitative tool that identifies biological agents and assesses the risk caused by them based on the probability of exposure and severity of harm. The tool also considers the risk management measures used in the workplace to reduce exposure. The magnitude of the risk to the employee's health, safety and well-being is expressed in terms and traffic lights in the model.

5.4.1 Legislation

Risk assessment at workplaces in Finland is required by the Occupational Safety and Health Act (738/2002). Based on this, the employer must identify work-related hazards and hazards, such as biological agents, in the workplace under its control and assess their significance for the safety and health of employees, as well as for reproductive health. Government decrees issued under the Occupational Safety and Health Act contain guidelines for preventing and reducing exposure to biological agents (933/2017 and 747/2020). In the case of activities which may involve exposure of workers to biological agents, the probability, nature, amount and duration of exposure and the severity of the potential harm shall be assessed. Based on these, the magnitude of the risk to the worker's health and safety is assessed and, if necessary, additional measures to prevent exposure and reduce the risk are decided.

Although biological agents have clearly been recognized as workplace risk factors by the legislation, the focus has traditionally been more on chemical and physical risks of work environments. There has been a lack of practical, user-friendly methods to recognize and evaluate the significance of exposure and risk. In Finland, the Finnish Institute of Occupational Health is finalizing a tool for workplaces to meet the requirements of Finnish legislation. Also in Europe, a consortium is developing algorithms to assess biological risks for Stoffenmanager® online chemical management tool.

5.4.2 Biological agents

Risk assessment begins by identifying potential biological agents that may pose hazards to workers. Biological agents are organisms derived from humans, animals or from the environment. The agents include bacteria, fungi, protozoa, parasites, prions and viruses that can cause some inflammation, allergy or

poisoning symptom. Biological agents also include their metabolites, breakdown products and constituents (e.g. endo- and mycotoxins). Exposure to biological agents can occur through the respiratory tract as aerosol and droplet infection, through skin, hands or mucous membranes as contact infection, and through oral ingestion into the digestive tract, from an animal bite or an insect sting. In addition to the disease-causing capacity (with or without the possibility of transmission between humans), toxicity of varying severity, or sensitisation of the exposed person, the health hazard caused by biological agents is affected by the amount and duration of exposure, simultaneous exposure to other factors weakening immunity, and the immunity and state of health of the exposed person. For the reasons mentioned above, the risks caused by biological factors are challenging for workplaces to assess and manage.

5.4.3 Classification of biological agents (4 groups)

The risk assessment must consider the Decree of the Ministry of Social Affairs and Health on the classification of biological agents (748/2020). Biological agents are divided into four groups according to the hazard they pose. The classification is based on the effect of biological factors on healthy workers. Effects on workers whose sensitivity may be affected by other causes, such as pre-existing disease, medication, immunodeficiency, pregnancy or breastfeeding, have not been considered in the classification. These personal or individual conditions must be acknowledged, preferably with help from occupational health professionals.

- Group 1 biological agent means one that is unlikely to cause human disease.
- Group 2 biological agent means one that can cause human disease and might be a hazard to workers; it is unlikely to spread to the community; there is usually effective prophylaxis or treatment available.
- Group 3 biological agent means one that can cause severe human disease and present a serious hazard to workers; it may present a risk of spreading to the community, but there is usually effective prophylaxis or treatment available.
- Group 4 biological agent means one that causes severe human disease and is a serious hazard to workers; it may present a high risk of spreading to the community; there is usually no effective prophylaxis or treatment available.

5.4.4 Subjects of risk assessment

For all work tasks that may involve exposure of workers to biological agents, the likelihood and severity of each identified hazard must be evaluated. The employer must assess the risks, considering not only its own employees, but also other operators and customers in the workplace's operating area. The Occupational Safety and Health Act defines the obligations of employees in the workplace regardless of the sector. The principal controlling employer shall, in the first instance, carry out a risk assessment of hazards and ensure that workers and

other persons working in the common space or associated environment have been informed of the biological agents present at work, safe practices and available risk management measures. Before starting work, every employer must also ensure at the shared workplace that a risk assessment has been carried out and that employees have been familiarized with the risks of work, the working conditions a the workplace, work equipment and its correct use, and safe working practices. The employer is obliged to limit exposure to biological agents to such a minimum that these agents do not cause serious health hazards or danger to anyone.

The law provides for cooperation in occupational safety and health matters, such as risk assessments, which refers to employers and employees working together. Occupational health professionals should also be involved, when needed. The involvement of workers in risk assessment is important, drawing on their knowledge and experience, especially during the identification phase of biological agents and when considering the suitability of risk management measures for their duties. Occupational health care expertise should be utilized in identifying biological agents and assessing the severity of exposure, verifying employees' symptoms and illness, and preventing the possible spread of infectious diseases. By the employer, the risk assessment of biological agents is compiled into a single entity, which is updated regularly and as situations change (e.g. because of an epidemic in the population).

5.4.5 Biological agent spreading as an epidemic

When an epidemic situation is ongoing in the population, workplaces must carry out a continuous case-by-case risk assessment, which considers possible local circumstances that reduce or increase the risk. At workplaces, employers must assess, considering the current epidemic situation, whether the risk of infection at work has increased compared to the rest of the population and if measures are needed to limit the risk of infection among employees and to protect safety and health. To assess the likelihood of exposure, workplaces need information on, among other things, the pathways of infection, the ability to cause disease, the potential for spreading and its detection, as well as the incidence of infections in the areas where the workplace operates. Workplaces need to be able to draw on healthcare expertise in their risk assessment.
The Finnish Institute for Health and Welfare (THL) monitors the infectious disease situation in the population, the prevalence and characteristics of microbes and, if necessary, provides information on epidemics.

An example of related links: https://thl.fi/en/topics/infectious-diseases-and-vaccinations/surveillance-and-registers/wastewater-monitoring

Wastewater monitoring produces information on the regional prevalence and any changes to coronavirus, influenza A- and B-viruses as well as RSV.

5.4.6 People at risk

Risk assessments at workplaces are primarily carried out considering healthy, adult persons. If particularly vulnerable workers (e.g. pregnant women or people with certain diseases) work at the workplace who may suffer serious health damage even in low-risk work, their risk assessment must be specified with the assistance of occupational health care. Identifying people belonging to risk groups is challenging at workplaces because their personal health information is not available to the employer. However, if the risk of infection has significantly increased for them, the employer must take occupational safety and health measures. If the risk cannot be managed to sufficiently low level at work, for example through protective measures, efforts must be made to arrange other work for the employee where there is no corresponding risk of infection.

When women of reproductive age are placed in work where there is a risk of exposure to biological agents, the worker must be informed of the presence of biological agents harmful to reproductive health already at the recruitment interview. The employer shall identify the risks posed by the agents referred to in this Regulation (see the link below) at work and assess their significance for the safety, health, pregnancy and breastfeeding of pregnant workers, workers who have recently given birth and workers who are breastfeeding. Biological agents posing such a risk include hepatitis viruses, herpes viruses, HIV viruses, listeria bacteria, cytomegalovirus, toxoplasma, chickenpox virus, rubella virus and parvo pox virus.

Link: Government Decree on the Protection of Pregnant Workers, Workers Who Have Recently Given Birth and Workers Who Are Breastfeeding from Factors Causing a Risk at Work (143/2024)

5.4.7 Risk assessment and management tool

To help employers to fulfil the requirements of the legislation and ensure safe work environment, the Finnish Institute of Occupational Health has prepared a semi-quantitative tool for risk assessment and management of biological agents. The tool considers the specific features of different occupations and sectors, and furthermore, the characteristics of different biological agents. In future, the tool is available as an Excel file from the Finnish Institute of Occupational Health for participants of an online training on biological agents. The Excel table should be supplemented according to exposure situations at the workplace and the magnitude of the risk should be assessed for each task.

Biological agents are identified and the risks they pose are initially assessed in terms of the severity of exposure. The various factors of exposure (microbe and its intrinsic harmfulness, source, route, intensity, duration and recurrence) are scored, and based on the scores, the severity of the exposure is determined to be either minor, harmful, or serious. The probability of exposure is added to the severity of exposure, whereby the magnitude of the risk is obtained from their intersection point in the risk matrix (Table 1).

Table 3. The risk table is read in such a way that the intersection of the points selected from the table describes the magnitude of the risk.

	Severity of exposure		
Probability	**Minor**	**Harmful**	**Serious**
Unlikely Rare exposure and no cases of illness have been reported	**Negligible risk**	**Low risk**	**Moderate risk**
Possible Some exposures, near-misses or individual illnesses have been reported	**Low risk**	**Moderate risk**	**Significant risk**
Probable Exposures occur frequently, and illnesses have occurred	**Moderate risk**	**Significant risk**	**Intolerable risk**

The impact of risk management measures on exposure is then considered. Various risk management measures have been scored in the tool, and the amount of residual risk is calculated from the risk management measures currently available in the work task. The magnitude of the residual risk is obtained when the points of the risk management measures are subtracted from the points of the severity of the exposure.

The residual risk level is expressed in terms and traffic lights: negligible/minor, moderate or significant/intolerable (Table 2). Scoring can also be used to test how the magnitude of the risk changes when alternative risk management measures are used. If changes are needed to reduce the risk, additional measures, their schedules and responsible persons must be entered in the excel sheet.

Table 4. The need for additional measures in relation to the magnitude of the estimated residual risk.

Magnitude of residual risk	Additional measures to reduce the risk
Negligible risk or low risk	No action is required, but the situation must be monitored to keep the risk under control.
Moderate risk	Measures must be taken to reduce the risk. Measures must be dimensioned and scheduled sensibly. If serious consequences accompany the risk, it is necessary to find out the probability of the event in more detail.
Significant risk or Intolerable risk	Risk reduction is necessary, and measures must be taken quickly.

5.4.8 Risk management measures

Taking measures to reduce or eliminate risk is risk management. Risk management aims to prevent health hazards and minimise medical costs and sickness absences.

The exposure of workers should be reduced primarily by administrative and technical solutions, but also by using personal protective equipment (PPE) where necessary. Removing, substituting or isolating of the biological agent, good ventilation of work premises, personal hygiene and cleaning, utilization of available vaccines or prophylactic medication, and the training of employees in risk management plays a key role in preventing health hazards caused by biological agents. “Stay at home when ill” policy at workplace is an efficient isolation technic against spreading of infective biological agents.

Personal protective equipment is introduced when sufficiently effective technical prevention solutions are not available or if they are awaited. The type and effectiveness of personal protective equipment are selected depending on the suitability and ability of the worker for the work. If respiratory protective equipment is required, it must be equipped with a particulate filter marked with the letter "P" to reduce exposure to biological agents carried by inhaled air. Respiratory protective equipment must fit and be worn tightly on the face to protect the wearer. It may be necessary to consult also occupational health professionals to ensure that the worker’s health status enables the use of PPE.

The employer must ensure that protective equipment, work equipment and cleaning equipment are cleaned regularly, especially when direct contact with the hazard has occurred. Work clothing and other protective equipment potentially contaminated with biological agents must be removed on departure from the work area and stored separately from other clothing and clean supplies. Where necessary, single-use personal protective equipment shall be used.

In this section, you should shortly review the main results or findings of the study/work.

5.4.9 Significance of the risk

When deciding on the significance and the acceptability of a risk, it is essential to consider how large a group of employees are affected by the consequences and how long-term the consequences are for the organisation. It must also be considered whether the risk may cause consequences for persons outside the workplace or whether there are employees of subcontractors or temporary agency workers at the site who are exposed to the risk of biological agent. The significance of the risk increases the larger the number of persons exposed to the risk.

In addition, the workplace can examine the significance of the risk from the point of view of the entire organisation, assessing the effects of the materialisation of the risk in relation to the fluency, profitability and productivity of work as well as stakeholder requirements. If the risk affects a large group of people and the consequences of the risk are long-term for the organization, the risk is considerable. In this case, it is necessary to reduce it, and measures must be taken as a matter of urgency.

Link: Risk assessment and management at the workplace workbook (Ministry of Social Affairs and Health and Finnish Centre for Occupational Safety and Health 2021)

5.5 Comparison of energy efficiency of air cleaning

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Abstract: Controlling respiratory infection transmission in buildings is vital for public health, especially during pandemics like COVID-19. Effective measures reduce community outbreaks and economic impacts. Identifying high-risk areas with poor ventilation and high occupancy is crucial for targeted interventions. HVAC systems, air cleaners, and UVGI play key roles in maintaining indoor air quality. However, these measures can increase energy consumption, necessitating a balance between infection control and energy efficiency.

5.5.1 Introduction

Managing the spread of respiratory infections within buildings is vital for public health, particularly during pandemics like COVID-19. Limiting transmission in offices, schools, and public venues helps prevent large-scale community outbreaks. Effective measures can also reduce sick leave's and healthcare expenses' economic burden.

Identifying areas with the highest transmission risk is essential for focused interventions. These high-risk zones typically include poorly ventilated spaces, crowded areas, and places where respiratory aerosol-generating activities like talking, singing, or exercising occur (Kulmala et al., 2024). By pinpointing these hotspots, building managers can implement better control measures, such as boosting ventilation, installing air purifiers, or limiting access during busy times (Vartiainen et al., 2024).

Building HVAC systems plays a crucial role in maintaining indoor air quality and controlling infection spread. During a pandemic, these systems should be optimized to increase outdoor air exchange and maintain proper humidity levels. Additionally, HVAC systems can be enhanced with air purifiers and UVGI to improve their infection control effectiveness. However, using air purifiers and increasing ventilation can lead to higher energy consumption, so it’s important to balance infection control needs with energy efficiency.

5.5.2 Identification of hot spots

We utilised the model presented by (Kulmala et al., 2024) in a daycare centre to estimate the transmission probability and the number of people at risk in all areas where children and their caregivers regularly spend time. The model proved useful in ranking and identifying hotspots and events within the building where the risk of infection transmission is increased due to favourable conditions or human

behaviour. Identifying these hotspots is essential for implementing effective control measures. Examples of this are presented in Figures 1 and 2.

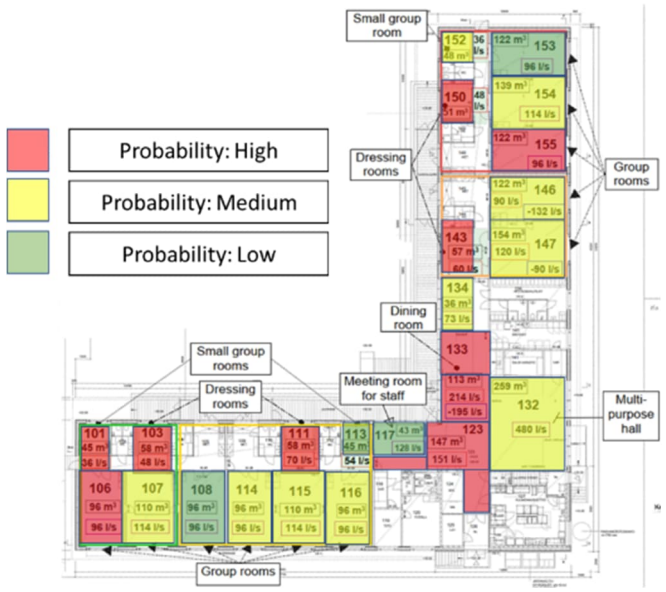

Figure 7. Transmission probability in different rooms in daycare centre A.

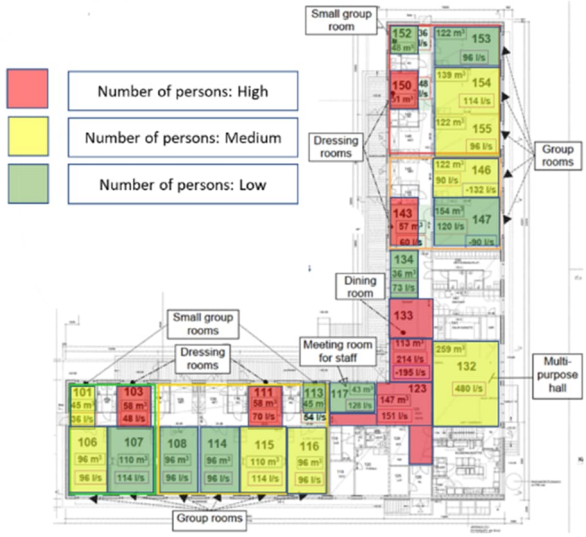

Figure 8. Number of people at risk in different rooms in daycare centre A.

As shown in Figure 7, the transmission probability varied between rooms and over time. The highest transmission probability was observed in crowded and poorly ventilated spaces, such as dressing rooms and occasionally in rooms where lunch is served. Conversely, the transmission probability is much lower in rooms with low occupancy or activity levels.

The picture changes somewhat when we examine the number of people at risk (Figure 8). While some rooms still rank as high relative risk, in some cases, the ranking of the room is lower.

5.5.3 Energy consumption of room air cleaners and HVAC system

Portable air cleaners (PACs) were strategically placed in two daycare centres in Helsinki, Finland. A total of 45 PACs were installed across 40 rooms and the electric power consumption of each unit was continuously monitored. We then determined the ventilation and heating energy consumption under three scenarios (Säämänen et al., 2024b):

- Scenario I: Current HVAC air flow rates,
- Scenario II: Current HVAC system with increased non-infectious air flow rates produced by PACs,
- Scenario III: Enhanced HVAC system with outdoor air flow rates adjusted to match scenario II's total non-infectious air flow rates.

There was a noticeable difference in the total electricity and heating energy consumption between the daycare centres and the scenarios (Figure 3). The data shows that the electricity consumption from the PACs was only a fraction (16 % in daycare centre A and 6 % in B) of the total energy consumption (electricity and heating) of the HVAC system. It is also seen that increasing the ventilation rates of the general ventilation by the amount produced by the air cleaners would roughly double the total energy consumption (Scenario III).

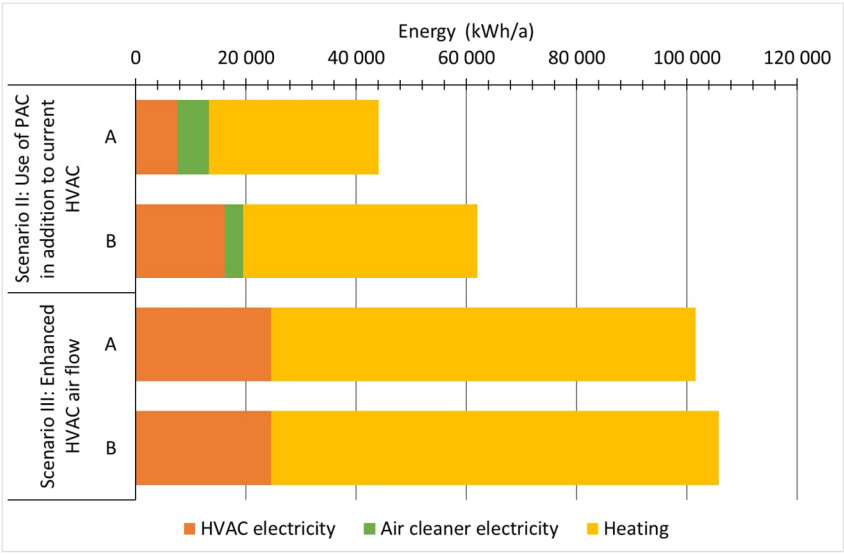

Figure 9. Comparison of annual energy consumption in kindergartens A and B.

5.5.4 Comparison of energy demand of UVGI and fibrous filter air cleaning devices

Additionally, we evaluated the power consumption of portable room air cleaners equipped with high-efficiency particle filters and compared it to in-duct UVC devices (Säämänen et al., 2024a). This study measured the energy use and clean air delivery rate (CADR) of the room air cleaners, while data on the electric energy demand for in-duct UVC devices was sourced from a previous study. To make a fair comparison, we established a common metric for their efficiency in controlling airborne viruses, based on the electric power required to generate one cubic meter per second of non-infectious air flow.

High-efficiency particulate filters in room air cleaners are effective at capturing airborne virus particles. Consequently, the measured CADR value was used to estimate the equivalent non-infectious air flow rate Q_{eq} for these room air cleaners.

$$Q_{eq} = CADR = Q_{device} \times \eta$$

The U.S. EPA's technical brief[6] and detailed evaluation reports provided data on the electric power consumption and airborne bioaerosol inactivation efficiencies of nine in-duct ultraviolet light devices (UVC1-UVC9). The inactivation efficiencies

[6] https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NHSRC&address=nhsrc/si/&dirEntryId=233212

for *Escherichia coli* MS2 bacteriophage were used to estimate the non-infectious air flow rate for viruses using the formula:

$$Q_{eq} = \varepsilon \times Q_{test}$$

where Q_{eq} in the equivalent non-infectious air flow rate (m^3s^{-1}); ε is the inactivation efficiency and Q_{test} is the air flow rate at which the inactivation efficiency is measured (m^3s^{-1}).

Specific power consumption S (Wsm^{-3}) for both UVC devices and room air cleaners was calculated using the measured electrical power consumption P (W) and estimated equivalent non-infectious air flow rate (m^3s^{-1}).

$$S = \frac{P}{Q_{eq}}$$

The calculated specific powers of portable room air cleaners and in-duct ultraviolet light inactivation devices are shown in Figure 4 and 5.

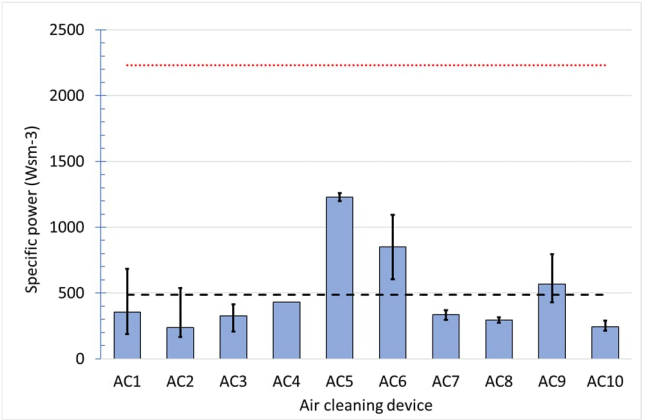

Figure 10. Specific power demand of room air cleaner models (AC1-AC11) in producing non-infectious air flow. Error bars in a) shows the minimum and maximum specific powers of individual devices in model group.

The specific power consumption of various air cleaner models showed significant variation, ranging from 166 to 1260 Wsm^{-3}. This variation is influenced by the design and components used in the room air cleaners, such as fans, particulate filters, and possibly activated carbon filters. On average, the specific power of all air cleaners was 465 $W{\cdot}sm^{-3}$, which is consistent with energy consumption reported in previous studies.

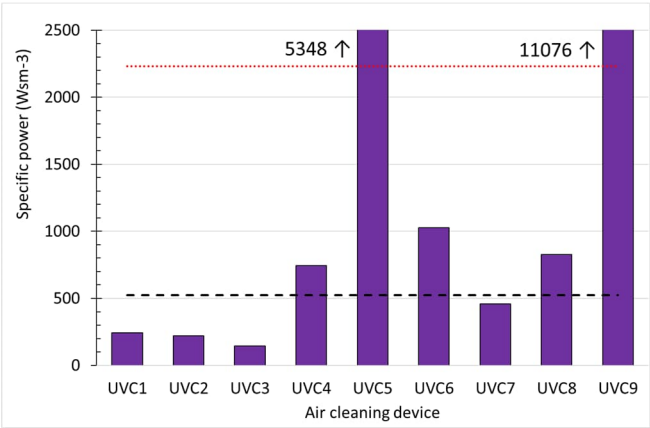

Figure 11. The specific power demand of in-duct UVC devices (UVC1-UVC9) in producing non-infectious air flow.

The specific power consumption of in-duct UVC devices varied even more than that of room air cleaners. The two highest specific power exceeded 5 000 Wsm^{-3}, while the lowest was 146 Wsm^{-3} (fig 1b). This wide range may be attributed to the selection of components (e.g., UVC source) and the unit's construction. Excluding these two extreme values, the average specific power (523 Wsm^{-3}) is comparable to that of room air cleaners when considering the inactivation efficiency of the MS2 bacteriophage. The UV-C flux needed to inactivate pathogens varies between species.

5.5.5 Discussion and Conclusions

The robust risk assessment model developed in the E3 project is an invaluable tool for pinpointing and ranking high-risk rooms and activities, which aids in selecting appropriate mitigation strategies, such as using room air cleaners. By focusing on the number of individuals at risk, this model helps prioritise actions and implement targeted measures to effectively reduce airborne infection transmission. This approach not only improves the overall safety of indoor environments but also ensures that resources are allocated where they are most needed, optimising infection control efforts.

Typically, HVAC airflow rates are designed to maintain good indoor air quality under normal conditions. However, airborne hazards from infectious aerosols may necessitate increasing airflow rates beyond the levels defined by building codes and regulations. During the COVID-19 pandemic, recommendations for improved ventilation suggest significantly higher non-infectious airflow rates, ranging from 14 l/s/person to 15-45 l/s/person (ASHRAE, 2023). Oversizing the HVAC system for such relatively infrequent events requiring enhanced ventilation can be costly and unsustainable. Barriers to using increased ventilation airflow rates with current HVAC systems include higher energy consumption and physical limitations within

the system (e.g., fans, heating/cooling coils, ducts, supply air inlets) may pose limitations when attempting to double the airflow rates using the existing HVAC equipment. Therefore, significantly increasing airflow rates with the existing HVAC systems may not be realistic for rapid response.

However, the options to quickly meet increased demand are limited. Two feasible alternatives are UVC devices using UV light irradiation and portable air cleaners (PACs) having efficient particle filters for airborne pathogens. When comparing additional non-infectious airflow rates produced by the HVAC system and PACs, the removal of carbon dioxide (CO_2) becomes a relevant consideration. Although devices with activated carbon filters are effective for several volatile organic compounds and ozone, they are not effective for CO_2. Consequently, while achieving the same non-infectious airflow rate, the HVAC system supplying fresh air results in lower CO_2 levels. Although this may not be critical when the base-level ventilation rate is sufficient, it could become an issue in poorly ventilated spaces. Other considerations with PACs include noise level, airflow patterns near the outlet contributing to the risk of drafts, as well as ease of maintenance and filter changes.

The specific power needed for UVC inactivation of MS2 bacteriophage was on average 520 Wsm^{-3}. This relatively low power requirement is due to the ease of inactivating single-stranded RNA viruses with UVC. The corresponding average power with portable air cleaners used in this study was somewhat lower, 465 Wsm^{-3}. Both methods showed large variations in specific power between different units.

UVC irradiation reduces the infectivity of microbes but does not remove them from the air. The efficiency of UVGI depends heavily on the microbe type. In contrast, the efficiency of air cleaners with high-efficiency particle filters for controlling airborne viruses is based on their particle removal efficiency and airflow rate, which are independent of the microbe type and environmental conditions, making them more predictable. Another advantage of high-efficiency particle filters is that they remove also other airborne particulate contaminants, thereby improving indoor air quality.

5.5.6 Acknowledgements

We would like to extend our heartfelt thanks to the staff of the daycare centres in Helsinki. We are also deeply grateful to the children and their families for their participation and patience. Additionally, we wish to express our sincere appreciation to the companies that generously provided the air cleaners used in this study.

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5.6 Effectiveness of surgical masks and respirators against respiratory infections

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EXTENDED ABSTRACT

5.6.1 Background

As humanity currently navigates the period between two pandemics, it is crucial to learn from the previous pandemic to better prepare for the next by identifying effective mitigation measures. A considerable amount of scientific literature has been written about masks, their effectiveness, and usage policies. A minority of the studies found no evidence of mask effectiveness during the COVID-19 pandemic or against respiratory infections more generally. These studies received significant attention in the media, leading many people to believe that masks are ineffective. Our goal was to review the literature to understand how mask effectiveness has been studied and the results of these studies. We also aimed to assess how much mask-wearing mitigates infections in individuals and communities. The gathered detailed information (Mäkelä et al. 2024) is vital for developing infection modelling tools.

The masks used during the COVID-19 pandemic included: a) woven cloth masks, b) non-woven masks without references to standards, c) surgical masks for medical use, fulfilling the standard EN 14683, and d) filtering half masks (FFP2 or FFP3), referred as “respirators” in this abstract. Types a) and b) lack standardized effectiveness information. Surgical masks are strictly regulated by medical device regulations and the standard EN 14683, while respirators are regulated by PPE regulations and the standard EN 149 in the EU.

5.6.2 Methods

We performed a narrative literature review using PubMed and Annals of Work Exposure and Health databases as well as publications collected due expertise in this field. Limited sources were used to select articles, not only to find if masks mitigate respiratory infections but also to assess their effectiveness. We collected 256 articles and reviewed 158. Exclusion criteria included expert opinions, non-disposable respirators, mask usability, decontamination, and ethical issues.

5.6.3 Results

Out of 158 articles, 149 studied effectiveness or efficiency, with 131 finding it.

Table 5. Summary of articles on mask effectiveness or efficiency

Article type	Number	Studied eff.	Eff. found	Eff. not found
All	158	149	131	25
Systematic reviews on trials in clinical or community settings	16	16	10	6
Narrative reviews	4	4	3	1
Reviews on filtration efficiency of the face mask materials	2	2	2	0
Reviews on transmission modes of SARS-CoV-2	1	1	1	0
Reviews on mask types	8	7	6	1
Reviews on fit testing	2	2	2	0
Masks as a source control on the face of the infected	28	27	26	1
Protection provided by the masks	40	39	35	4
Effectiveness of the mask mandates	29	28	25	3
Adherence to mask usage	9	4	3	1
The impact of tight fit of the respirator on effectiveness	13	13	11	2
The ability of seal check to identify respirator leakage	6	6	0	6

Eff. = effectiveness, and in laboratory test-based articles efficiency

5.6.4 Discussion and conclusions

The narrative perspective on mask effectiveness was enlightening. Each study's context must be understood before summarizing. Assessing mask effectiveness from infection data is significantly influenced by study conditions. The variability in study conditions can explain why some randomized controlled trials in clinical or community settings, as well as mask mandate effectiveness studies, found no evidence of effectiveness, while others reported high effectiveness (e.g., reduction of infection risk by 47% or 70% during the study period). Systematic reviews of trial studies in clinical or community settings showed effectiveness in 10 out of 16 studies, and 20 out of 23 studies found mask mandates effective.

Cloth masks are not ineffective, but surgical masks provide better protection, and respirators offer superior protection. Respirators protect against airborne particles including viruses. The filtering efficiency and air leakage of other masks make them poorer against airborne viruses. Masks are more effective when worn by the infected than by those needing protection. It is far superior when both

parties wear masks. The assigned protection factor is 1-2 for surgical masks, 10 for FFP2 masks, and 20 for FFP3 masks. We found no information contradicting these factors. Even relatively inefficient masks can lower pathogen concentration in exhaled air or direct it away from people in front of the mask wearer. The studied non-woven masks without standard markings did not meet the standard requirements.

Fit testing is essential for respirator effectiveness. However, even without fit testing, respirators are more effective than surgical masks. Beards reduce respirator effectiveness and make passing of the fit tests difficult. “Seal checks” were found rather ineffective in all six studies. A seal check is a procedure where the respirator user checks the donned respirator for leaks using their own breath.

It is important that nations prepare for the next pandemic with effective personal protective equipment. As part of this preparation, it is crucial for people to understand that mask-wearing can significantly reduce respiratory infections. The choice of masks should depend on the evaluated risk. Notable, wearing respirators can reduce exposures to respiratory diseases that are transmitted through air. As of now, we do not know the level of risks the next pandemic will pose, so we must be prepared for a pandemic worse than COVID-19.

5.6.5 References

Mäkelä E.A., Jussila K., & Laitinen S. (2024). *Effectiveness of surgical masks and respirators against respiratory infections.* Finnish Institute of Occupational Health. ISBN (PDF): ISBN 978-952-391-172-7. To be available at Julkari https://www.julkari.fi/

5.7 Evaluation of UVGI air purifier in laboratory conditions

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Abstract: This study evaluates the performance of a portable UVC device in disinfecting air, comparing its energy consumption and effectiveness against surrogate microbes to traditional fibrous filter devices. The performance of an experimental UVGI-based portable air cleaner was evaluated in a controlled test room, focusing on microbial inactivation efficacy. The study measured the air cleaner's effectiveness, energy consumption, and ability to detect microbes using advanced instrumentation. The UVC experimental device was more effective at inactivating MS2 bacteriophage compared to *B. atrophaeus* bacterial spores, but it consumed significantly more energy than fibrous filters. Additionally, the presence of d-limonene did not result in secondary aerosol formation, and the clean air delivery rates measured with WIBS were lower than those measured with microbiological methods.

5.7.1 Introduction

The COVID-19 pandemic has underscored the critical need for resilience in both societal and economic structures. It has become evident that no single countermeasure is sufficient to combat such global health crises effectively. Consequently, developing comprehensive protection strategies against pandemics is essential. Among the various routes of pathogen transmission, the air transmission route has garnered significant attention due to its potential for widespread impact. This E3 project focuses on the air transmission route, emphasizing the sustainability of ventilation and air filtration/purification strategies to achieve "pathogen-free" and energy-efficient HVAC systems and low-pressure air filtration.

Achieving "pathogen-free" indoor air can be accomplished through air filtration or the disinfection of infectious aerosols using germicidal ultraviolet light (UVGI). Germicidal ultraviolet (UVGI) disinfection employs ultraviolet energy to inactivate microorganisms. UVC (200 – 280 nm) can be utilized in several ways to disinfect air: creating a disinfection zone above the heads of people in a room using upper-room UVC, installing in-duct UVC sections in HVAC systems to inactivate airborne viruses in recirculated air, or equipping room air cleaners with UVC lamps to disinfect the air in a single room.

In this laboratory experiment, we focus on the performance of a portable UVC device. We studied the device's performance against selected microbes in a test room, paying attention to the possible formation of secondary products. We also

measured the energy consumption and compared it with that of fibrous filter devices. Additionally, laboratory experiments were conducted to evaluate how well novel measurement instrumentation could detect microbes.

5.7.2 Materials and Methods

The performance of the experimental UVGI-based portable air cleaner was evaluated in VTT's air cleaner test room, a 30 m³ stainless steel chamber. The chamber temperature was maintained between 21.7°C and 23.5°C, with relative humidity between 10.1% and 13.8%. A fan ensured even air mixing within the chamber.

The experimental UVC air cleaner (Figure 12) featured 10 UVC lamps (OSRAM Puritec HNS S/E 11 W) in 5 sections, each with a dominant wavelength of 254 nm and a radiant power of 3.6 W. The system included 5 stainless steel mesh units, with or without photocatalyst treatment (estimated area: 2.43 m²). An external fan provided an airflow rate of 60 l/s (216 m³/h), corresponding to a fan power of 31 W and a pressure drop of 27 Pa. When the UVC lamps were activated, the system's total power demand was 170 W.

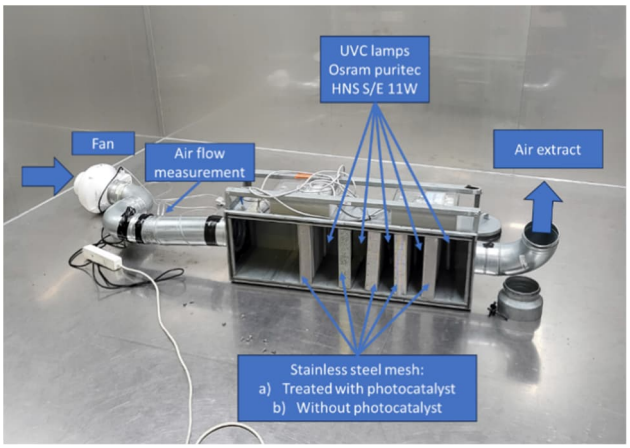


Figure 12. Essential parts of tested experimental UVGI air purifier.

A pneumatic atomizer produced the challenge aerosol from a solution containing approximately 8 × 10⁸ *Bacillus atrophaeus* spores/ml and 1 × 10⁸ MS2 bacteriophage viruses/ml. D-limonene was used as a VOC source in some experiments, with target concentrations between 600–1200 µg/m³.

Microbial inactivation efficacy was tested in four scenarios:

- UV with photocatalyst
- UV without photocatalyst
- UV with photocatalyst and limonene
- Reference measurement without UV or limonene

Each test followed three steps: 1) Atomize microbial aerosol for 5 minutes and let settle for 7 minutes, 2) Collect a 3-minute microbial air sample, then activate the air cleaner, 3) Collect another air sample after 30 minutes, then flush the test chamber.

Airborne microbe samples were collected using a BioSampler impinger (SKC Inc, USA) at a flow rate of 12.5 l/min with 5 ml peptone-saline solution. Samples were cultured on Petrifilm AC and Plate Count Agar (PCA) plates. MS2 bacteriophage counts were determined using *Escherichia coli* as the host bacteria.

The Wideband Integrated Bioaerosol Sensor-New Electronics Option (WIBS-NEO) measured bioaerosols using UV flashlamp sources to excite fluorescence in particles, with detection wavebands optimized for common bioaerosol components. The device measures fluorescence in three channels: A, B and C. In channels A and B, UV-source with a wavelength of 280 nm is used, and fluorescence is detected at emission bands of 310–400 nm and 420–650 nm, respectively. In channel C, a 370 nm UV-source is utilized and emission is detected in the range of 420–650 nm.

The Scanning Mobility Particle Sizer (SMPS, TSI) measured the size distribution of airborne submicron particles, providing near real-time nanoparticle concentrations. In addition, Another SMPS (TSI Inc., USA) measured number size distributions of submicron particles with a range of 12–414 nm and a time resolution of ~3 minutes.

The Time-of-Flight Aerosol Chemical Speciation Monitor (ToF-ACSM, Aerodyne Research Inc) provided long-term monitoring of submicron aerosol composition with high temporal resolution and mass resolving power.

5.7.3 Results

The performance of the UVC air cleaner was evaluated by measuring the reduction of viable microbes in the test chamber over a 30-minute period. Figure 13 illustrates the microbe reduction achieved with different test setups.

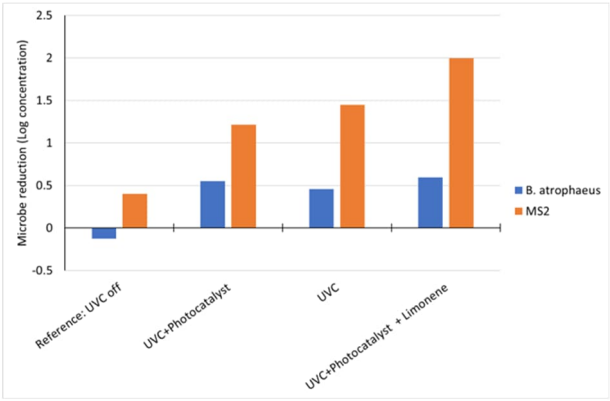


Figure 13. Microbe reduction with different test set-ups.

As can be seen in Figure 2, the reduction of *B. atrophaeus* was much less than log1 indicating that they hardly can be inactivated with the used UVC device in 30 minutes.

The calculated CADR (Clean Air Delivery Rate) values for the UVC device showed high variation between repeated tests. For MS2, the effective clean air flow rate ranged from 52% to 100% of the system's airflow rate, while for *Bacillus atrophaeus*, it ranged from 37% to 46%. **Error! Reference source not found.** present the measured CADR values for different setups and repeated tests, accounting for natural decay and inactivation.

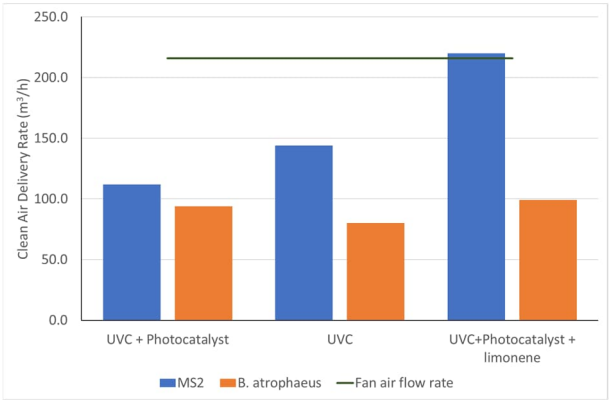


Figure 14. Calculated clean air delivery rates in different experiment set-ups for MS2 and *B. atrophaeus.* Natural decay and inactivation is considered when calculating the results.

The specific power of the UVC device was calculated to compare energy consumption. The specific power varied between 2300 and 6300 W/(m³/s) (Table 6).

Table 6. Measured specific power for different experimental set-ups

Experimental set-up	Specific power [W/(m3/s)]	
	MS2	*B. atrophaeus*
UVC + Photocatalyst	4500	5362
UVC	3500	6300
UVC + Photocatalyst + limonene	2291	5091

Based on the SMPS measurements, the combination of limonene and UVC did not generate nucleation mode particles.

Clean air delivery rates have been calculated based on the measurement data of WIBS for particles with a diameter at least 1 µm. The threshold of 9 standard deviations was used to classify the fluorescence of particles. The results illustrated in Figure 15 (a, b) show that the CADRs of A fluorescence channel, where *Bacillus atrophaeus* should appear are lower than CADRs of fluorescent and all particles. However, Figure 15 (c) indicates that the CADRs of A fluorescent particles increase the most when the UV device is utilized. The average CADRs of different measurement types are presented for all, fluorescent and channel A fluorescent particles in Figure 16, where all the measurements utilizing UV-device show low but higher than reference CADRs.

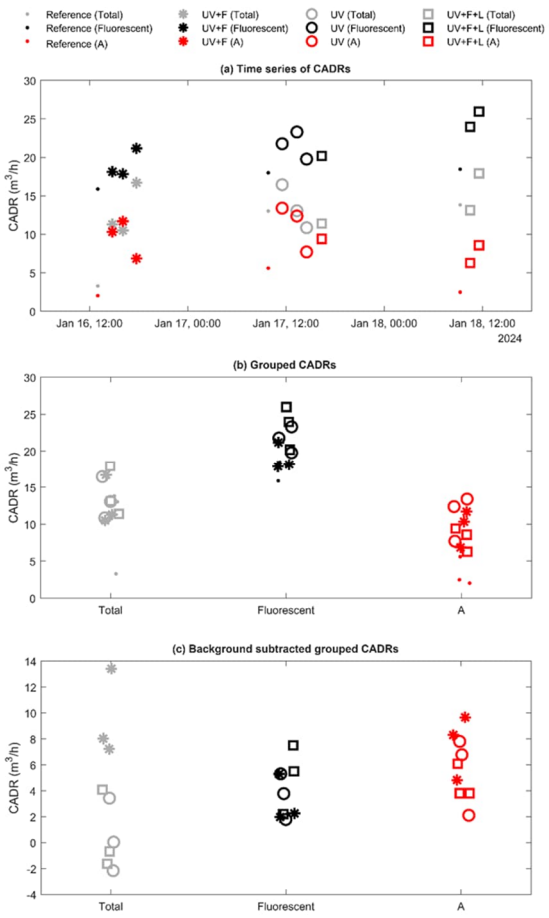
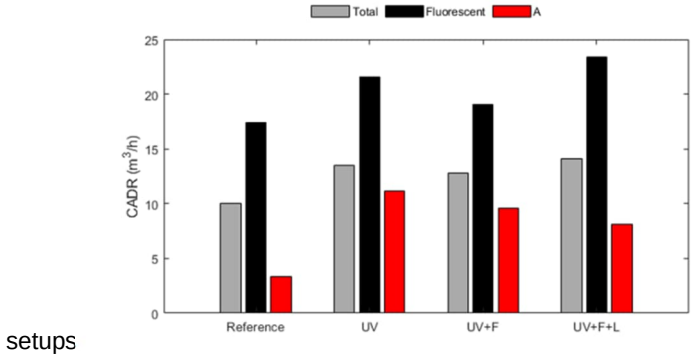


Figure 15. Clean air delivery rates (CADRs) are calculated based on the measurement data of WIBS for particles with a diameter of at least 1 µm. The same results are presented as a time series (a), grouped according to the type of observed particles (b) and grouped the same way but as background-subtracted values.



setups

Figure 16. The average clean air delivery rates (CADRs) of different measurement types calculated based on the measurement data of WIBS for particles with a diameter at least 1 µm.

The total fluorescent fraction and fractions of different fluorescence channels are illustrated in Figure 17, where one measurement utilizing UV-device is presented as an example. The figure shows that most of the particles have a size between 0.5 and 0.99 µm, while the fraction of fluorescent particles is significantly larger in the size bin of 1.0–2.49 µm. The number of A fluorescent particles is still greater in the smaller size bin. The largest size bin of 2.5–4.99 µm has very few particles compared to the smaller bins.

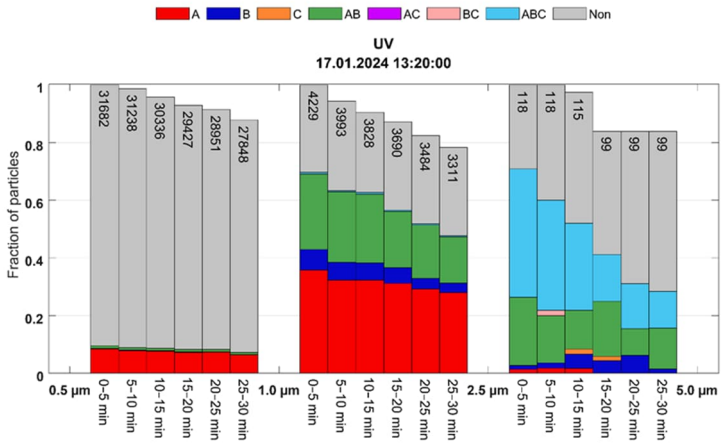


Figure 17. Fractions of fluorescence channels as a function of time and particle size in measurement utilizing UV-device. The total number of particles in each size bin during a certain time period are presented numerically.

Submicron particle composition during the experiments was measured with the ToF-ACSM. Results indicate small amounts of organics, and chloride likely originating from the aerosolized bacterial solution.

Limonene decay was measured in the case where UVC air purifier was equipped with photocatalyst, Limonene decay rates according to Tenax tube sampling were 0.75 h^{-1} and 0.54 h^{-1}. These decay rates are equivalent to the clean air delivery rate of 22.5 m^3/h and 16.2 m^3/h. Limonene concentrations were also measured in one reference case and in decay with PID instrument (ppb RAE, RAE systems Inc.). The limonene decay rate in the reference case was 0.14 h^{-1}, with UVC on 0.32 h^{-1}. The effect of photocatalyst together with UVC radiation was 0.18 h^{-1} resulting in the CADR value of 5.4 m^3/h.

5.7.4 Discussion and Conclusions

The UVC (254 nm) experimental device was much more efficient in inactivating MS2 bacteriophage than the *Bacillus atrophaeus*. The measured clean air delivery rate for MS2 varied between 112 - 220 m^3/h while the air flow rate through the system was 216 m^3/h. For *B. atrophaeus* the measured clean air delivery ranged from 80 m3/h to 99 m^3/h. UVC radiation effectively inactivates various viruses and bacteriophages, reducing their ability to infect hosts and replicate (Thornton et al., 2022).

If we compare the efficiency of the tested UVC experimental to the theoretical efficiency of fibrous filters using ASHRAE 241-2023 recommendation even quite modest fibrous filter can produce the same performance. In addition, the experimental UVC device consumed quite a lot of energy, so that the specific power of the device was much higher than a comparable fibrous filter air cleaner (Säämänen et al., 2024).

In some tests we added d-limonene to the challenge aerosol to see the effect of VOCs on the performance of the device. In these tests, we did not observe secondary aerosol formation. Even though the device was equipped with photocatalytic filters, the decay rate of the limonene was very low. The observed limonene decay rate measured with sorbent tubes (Tenax TA-Carbopack B + TD-GC-MS) was slightly higher than that measured with PID detector.

Clean air delivery rates (CADRs) measured with WIBS were much lower than those measured with microbiological methods. However, the CADR of A fluorescent particles was found to increase the most when UVC device was utilized. Consequently, it is possible that the fluorescence of bacteria died at the beginning of the half hour measurement might fade during the measurement. The fading time of fluorescence after a bacterium dies could be interesting topic to investigate further.

5.7.5 Acknowledgements

We acknowledge Mr. Risto Salin from Inspector Sec Oy for providing the UVC air purifying device experimental type used in this study.

5.7.6 References

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5.8 Performance of air filters against airborne pathogens

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Abstract: This article reviews the size distribution of airborne particles containing SARS-CoV-2 RNA and the effectiveness of air filtration systems in various settings. It highlights the importance of air filters in reducing airborne contaminants and examines the survival of pathogens within filter materials. The study evaluates different air filtration and inactivation approaches, including “catch,” “kill,” and “catch and kill” methods, through a comprehensive laboratory measurement campaign. Studies show that filtration efficiency for bioaerosols and inert particles is similar, with efficiency correlating to particle size and filter type. The air filter coatings used in this study do not impede the filters’ ability to capture particles, maintaining their effectiveness in removing aerosols from the air.

5.8.1 Introduction

The presence of infectious airborne particles has been a critical area of study. Air filtration systems play a crucial role in reducing airborne contaminants, including pathogens like SARS-CoV-2. This article reviews the findings from various studies on the size distribution of airborne particles containing SARS-CoV-2 RNA. In addition, the article reviews the influence of air filters in field tests, focusing on their effectiveness in different settings and the survival of pathogens within filter materials. This part of E3 study aims to evaluate the benefits of various air filtration and inactivation approaches, including "catch", "kill", and "catch and kill" methods, in terms of infection control. A comprehensive laboratory measurement campaign will be undertaken to assess the particle size-dependent efficiency of air filters and inactivation solutions against bioaerosols, with particular attention to ventilation systems that utilize return air, such as those in public transport.

5.8.2 Size Range of Room Air Particles Containing SARS-CoV-2 RNA

Recent studies have extensively examined the presence and distribution of SARS-CoV-2 RNA in airborne particles within hospital environments. These findings are crucial for understanding the potential for airborne transmission and for developing effective air filtration strategies.

Several studies have identified SARS-CoV-2 RNA in all three size fractions examined (<2.5 µm; 2.5–10 µm; >10 µm) in hospital rooms. This broad size range indicates that the virus can be carried by a variety of particle sizes (Figure 1), which has significant implications for air filtration and infection control measures (Stern et al., 2021b, Stern et al., 2021a, Birgand et al., 2020, Santarpia et al., 2022). Ehtezazi et al. (2021) focused on aerosols generated by standard dental procedures and found that the majority (>99%) of aerosol-generating procedure

(AGP) particles were <0.3 µm in diameter (Ehtezazi et al., 2021). These particles remained at elevated levels around the dental team during procedures, highlighting the potential risk in dental settings. Chia et al. (2020) detected SARS-CoV-2-containing particles in size ranges >4 µm and 1–4 µm supporting the presence of the virus in various particle sizes (Chia et al., 2020). Groma et al. (2023) observed a bimodal distribution in the size variation of SARS-CoV-2 RNA copies for particles sized 0.07 to 8 µm (Groma et al., 2023). The study highlighted that viruses are more likely to exist in the 0.5–1 µm size range.

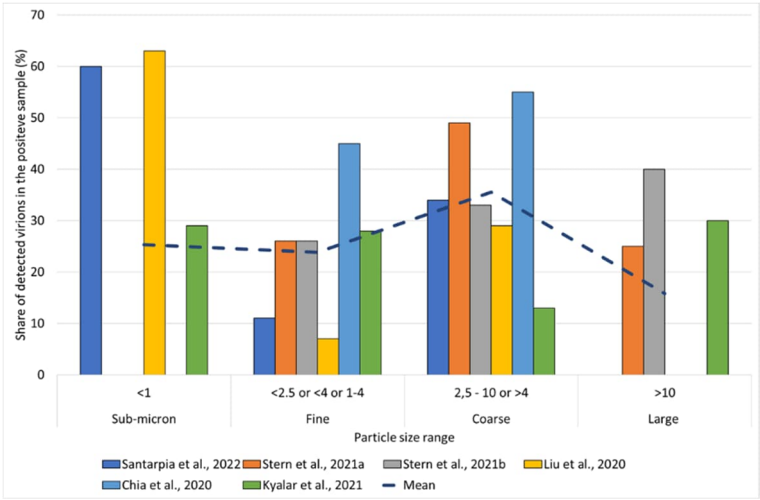

Figure 18. Detected SARS-CoV-2 RNA in different aerosol size ranges.

5.8.3 Filtration of bioaerosols

Studies comparing the filtration efficiency of bioaerosols, and inert particles have shown similar behaviour. Particles with similar aerodynamic diameters are filtered with similar effectiveness, regardless of whether they carry viable bacteria (Miller-Leiden et al., 1996, Eninger et al., 2008, Liu et al., 2009). This indicates that particle filtration efficiency can be a reliable indicator of microbial filtration efficiency (Pavard et al., 2022).

Various studies have tested the efficiency of air filters in capturing SARS-CoV-2 and other viral particles. It is found that F8 filters can retain dried SARS-CoV-2 virus-containing aerosols, but wet filters allow virus propagation (Saccani et al., 2022). It has also been demonstrated that high-efficiency residential HVAC filters are effective at capturing airborne virus particles, with efficiency correlated to MERV ratings (Zhang et al., 2020).

Air filtration is a widely implemented method to remove particles from air streams with known efficiencies. Studies have demonstrated that air filters used in residential HVAC systems are effective at capturing airborne virus particles, with

viral filtration efficiency correlated to the filter's general filtration efficiency rating [1]. High-efficiency particulate Air (HEPA) filters and higher-rated filters have shown filtration efficiencies greater than 99.99% for several pathogens [2] [3] [4] [5]. Additionally, filters with a Minimum Efficiency Reporting Value (MERV) 14 rating have been shown to achieve viral filtration efficiencies of over 95%.

ASHRAE defines a method to determine the infectious aerosol removal efficiency. It is based on the particle removal efficiency of the air filter in three particle size ranges: 0.3 – 1 µm, 1.0 – 3.0 µm and 3.0 – 10 µm. Each size range has a weighting factor with the highest value in the coarse size fraction (ASHRAE, 2023). Examples of some filter-type infectious aerosol removal efficiencies are shown in Table 1.

Table 7. Filtration efficiencies and pressure loss of air filters at the standard air flow rate of 0.944 m^3/s. Particle size ranges and calculated infectious aerosol removal efficiencies are according to ASHRAE 241-2023 (Säämänen et al., 2023).

Air filter type and classification	Pressure loss (Pa)	Efficiency% 0.3 – 1 µm	Efficiency% 1 – 3 µm	Efficiency% >3 µm	Infectious Aerosol Removal Efficiency%
G3	74	3	54	98	0 #)
M5	45	13	60	99	0 #)
F7	91	68	96	100	89
F7 combi *)	150	69	97	100	90
F9	160	89	100	100	96
E10	200	98	99	100	99

*) combined particle and activated carbon filter
#) mechanical fibrous filters with classification lower than about M6 (MERV-A 11) shall be assigned a value of zero (ASHRAE 241-2023).

5.8.4 Survival of pathogens within filter materials

Wenke et al. (2017) investigated the viability of various pathogens in different filter materials (Wenke et al., 2017). They found that the survival in filter material varied significantly with different pathogen types. Most of the studied pathogens had a short survival time, from hours to less than one day. On the contrary, *S. aureus* remained infectious for four weeks in both the prefilter and secondary filter of prototype 1 (polyester G4 + glass fiber F9) but not in prototype 2 (synthetic-

organic fiber G4 + glass fiber F9). A 1000-fold decrease in colony-forming units per millilitre (cfu/ml) was achieved within the first week, followed by another 100-fold reduction after four weeks. In prototype 2, *S. aureus* was viable after one week. The study concluded that pathogens can survive on filter materials for extended periods, necessitating the use of personal protective equipment during filter changes.

Coatings with antimicrobial properties are proposed to decrease the survival of pathogens in filter materials. Watson et al. (2022) explored The use of chlorhexidine digluconate (CHDG) coatings on filters was effective in killing pathogens and maintaining antimicrobial activity throughout the filter's operational lifetime (Watson et al., 2022). On the contrary Nazarenko (2020) discussed the limited impact of antiviral properties on the removal of viable SARS-CoV-2 virions from the air (Nazarenko, 2020). The study noted that particles tend to deposit on previously collected particles, reducing direct contact with antiviral substances on the filter material. They questioned the added value of imparting antiviral properties to HEPA-filter materials unless there is direct contact with these filters during or shortly after use.

5.8.5 Measurements with antimicrobial coating of HVAC air filters

Fibrous filters treated with antimicrobial coatings have entered the market. As previously mentioned, there is conflicting information regarding their impact on filter performance. As part of the E3 project, we aimed to investigate the effect of antimicrobial coatings on the efficiency and pressure drop of different types of fibrous filters.

The performance of two coated and uncoated air filters (class G4 and F7) was studied in the air filter test rig. Filtration efficiencies of the filters were determined by measuring the size distribution of challenge aerosol with an optical particle size analyser (PMS LAS-X II) alternately upstream and downstream of the filter. Diethyl-hexyl sebacate (DEHS) challenge aerosol was used as a liquid phase aerosol defined in EN 16890-2 standard in a test rig (Figure 2). The nominal air volume flow rate of 0.5 m3/s was used for tests. The pressure drop of the filters was measured with a flow rate of 50 %, 75 %, 100 % and 125 % of the test air flow rate.

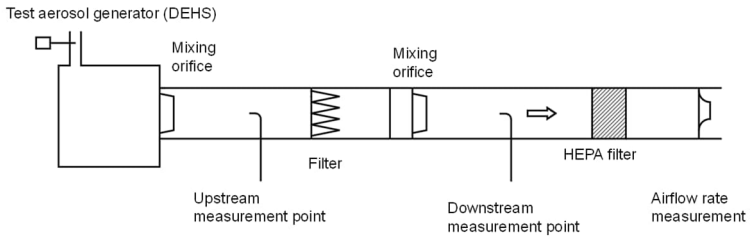

Figure 19. Test system for testing the performance of coated and uncoated air filters.

The study compared two types of filters: a coarse filter (G4) and a fine filter (F7). Both filters were tested in their uncoated and coated forms. The measurement results indicated that the separation efficiencies of the filters remained unchanged regardless of the coating (Figure 3). However, the pressure drop of the coated fine filter (F7) increased slightly (Figure 4).

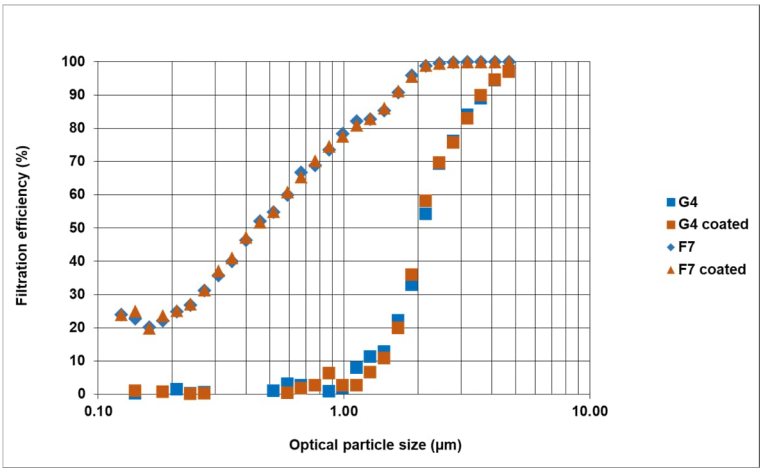

Figure 20. The measured filtration efficiencies of the uncoated and coated forms of tested air filters.

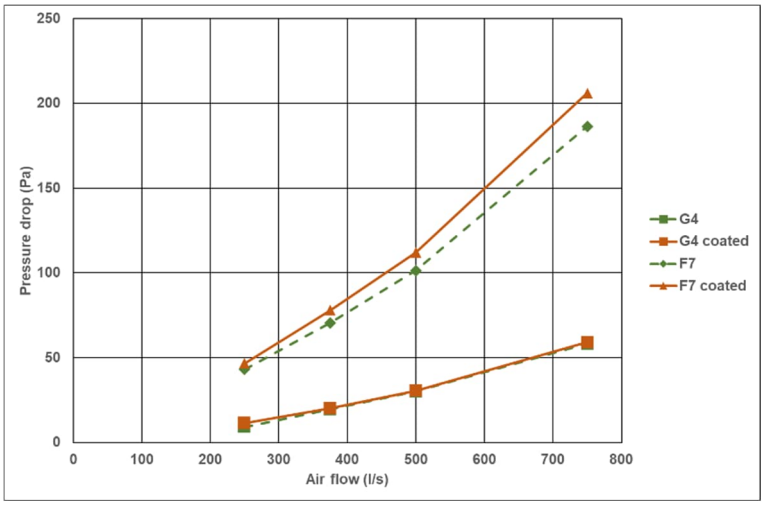

Figure 21. The dependence of the pressure drop on the airflow rate of the measured uncoated and coated forms of tested air filters.

Based on these measurements the infectious aerosol removal efficiency for the tested fine filter was 76%. Coarse filter has no classification for infectious aerosol removal efficiency according to AHSRAE 241-2023.

5.8.6 Conclusion

Understanding the size distribution of virus-laden particles and the performance of different filters is crucial for improving infection control measures in healthcare settings. The presence of SARS-CoV-2 RNA in airborne particles across various size ranges highlights the complexity of airborne transmission. Detecting the virus in particles smaller than 2.5 µm and larger particles underscores the need for filters that can efficiently capture a broad spectrum of particle sizes. The comparative analysis of bioaerosol and inert particle filtration efficiencies reveals that particles with similar aerodynamic diameters exhibit comparable filtration behaviours, irrespective of their biological viability. This finding underscores the reliability of particle filtration efficiency as a proxy for microbial filtration efficiency. In the context of viral particle capture, field tests have demonstrated that quite modestly rated air filters, like MERV-13 comparable to F7-F8, significantly improve air quality by removing aerosol particles.

ASHRAE's methodology for determining infectious aerosol removal efficiency, based on particle removal efficiency across three defined size ranges, provides a robust framework for evaluating filter performance. The highest weighting factor is attributed to the coarse size fraction, emphasising its critical role in infectious aerosol filtration. Empirical data from various filter types indicate that high-efficiency filters, such as F9 and E10, achieve superior infectious aerosol removal

efficiencies, with values reaching up to 99%. For F7 filters estimated infectious aerosol removal efficiency is about 90%. These insights highlight the critical importance of selecting appropriate air filtration systems to enhance indoor air quality and mitigate the transmission of infectious agents.

The survival of pathogens within filter materials is another critical aspect. Research indicates that while most pathogens have a short survival time on filter materials, some, like *S. aureus*, can remain viable for extended periods. The introduction of antimicrobial coatings on fibrous filters has generated interest due to their potential to enhance air quality by reducing microbial load. However, their impact on filter performance remains a subject of debate. Coatings with antimicrobial properties can enhance filter performance, but their practical benefits may be limited in certain scenarios.

Our investigation focused on two types of filters: a coarse filter (G4) and a fine filter (F7), both in their coated and uncoated forms. The filtration efficiencies were assessed using a DEHS challenge aerosol, with measurements taken upstream and downstream of the filters. The results indicated that the antimicrobial coatings did not alter the separation efficiencies of either filter type. This finding suggests that the coatings do not impede the filters' ability to capture particles, maintaining their effectiveness in removing aerosols from the air. However, the study revealed a slight increase in pressure drop for the coated fine filter (F7). This increase in resistance could be attributed to the additional layer introduced by the antimicrobial coating, which may somewhat obstruct airflow.

5.8.7 Acknowledgements

We like to acknowledge Peter Nordlund from Filterpak Oy for providing coated and uncoated filters used in this study.

5.8.8 References

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6 Health-safe buildings: technology, human and market aspects

6.1 Overview to chapter ‘Health-safe buildings’

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Abstract: Chapter ‘Health-safe buildings: technology, human and market aspects’ gives overview on the considerations of heath-safe buildings done in the E3 project, the studies on technological, human and market aspects going beyond Covid-19 to overall health-safety of indoor environment.

6.1.1 Introduction

When Covid-19 turned into a pandemic, national restrictions of assembly in public spaces were set by governments. Finnish government made no exception for that. The restrictions varied from moment to moment, but the principle was the same: the maximum allowable number of people in indoor spaces was limited to a number that was essentially smaller than that before the pandemic. In one moment, the maximum number was given as a figure that was independent on the volume of the space, in another moment, the maximum number could be derived from the requirement of minimum distance between persons in the space, etc (for details, see the press releases by the Ministry of Social Affairs and Health on Covid-19 in Finland). An overarching aspect for the restrictions was that the link between the restrictions and the real risk of being transmitted by SARS-CoV-2 virus was very weak. Therefore, many people felt that the Finnish Government overreacted to the pandemic and that the restrictions of assembly made more harm than good for the society, in general.

While there might have been good arguments for the given restrictions during Covid-19 due to the weak preparedness of society for a pandemic like that, we in the E3 project consortium thought that science and technology must be harnessed

to increase the safety of indoor spaces against future epidemics and pandemics. We visioned that the indoor air quality should be real-time monitored by sensors to see whether there are pathogens in the air and, if yes, how much. Based on these real-time measurements by IoT solutions, mitigation actions against the spread of pathogens would have been launched. Maximum allowable number of people in a room would depend on the indoor air safety in that moment of time, and that would be communicated to the users of room in a human friendly manner. In short, an idea of health-safe smart building was created.

During the Covid-19 pandemic, there were market interests towards smart systems that could connect the restrictions of assembly with the real risk assessment of safety in the space in question. Accordingly, we started in the E3 project to work towards such an integrated system of solutions, in accordance with our project plan. We estimated that the business potential for such smart systems would be the highest in office buildings and titled the work 'smart office'. After the pandemic had been stated of being over, the market interest towards such smart office solutions faded away. Owners and tenants of office and other real estate buildings started to be more worried about how to have customers and workers back to buildings than the health-safety of rooms. Hybrid-work become a new normal in offices resulting in that offices are not so crowded than before the Covid-19 pandemic.

In the new market situation, we were forced to redesign our smart office work and focus either on more general technology, human, and market aspects of health-safe buildings, or on more specific topics within the concept of smart office. These studies go beyond SARS-CoV-2 to overall health-safety mitigating the spread of pathogens in indoor environments. We still believe that in the long run there will be market need for solutions of health-safe smart offices and that the work done in the E3 project is a step towards such solutions.

Main research results of E3 project related to the smart office work of project are reported in this chapter 6 'Health-safe buildings: technology, human, and market aspects' and in chapter 7 'Controlled micro-environment in office rooms'. Papers in this chapter represent results of more generic research and development work while the controlled micro-environment is a specific approach of improving health-safety in office rooms.

6.1.2 Overview on papers in the chapter

The first research paper of the chapter by Uusitalo and Paasi presents the concept of health-safe smart building, where health-safe smart buildings integrate various technologies to promote healthy environments, mitigate adverse health outcomes, and enhance safety performance. This conceptual work could work as a framework for future research on the subject.

Human aspects of health-safe buildings are covered in the paper by Nuutinen, Paasi and Rökman. The paper gives design principles related to human factors and user acceptance for the development of solutions mitigating the spread of pandemic/epidemic in indoor spaces, the design principles given as User

Experience (UX) Vision and Goals together with context-dependent specifications for hospital, office and day care environments.

The last two papers of the chapter by Mantere and Puhto are about market aspects of health-safe buildings. The first one examines whether offering a health-safe and high-quality indoor environment can serve a competitive advantage for office property owners, the study focusing on tenants' perceptions on the importance of such indoor environments when choosing an office space and their willingness to pay for such environments. The latter study aims to identify the key barriers and drivers affecting the diffusion of innovations improving indoor environmental quality in the real estate sector. Along with the barriers and drives, opportunities for commercializing such solutions have been identified.

6.1.3 References

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6.2 Concept of Health-Safe Smart Building

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Abstract: A concept of smart health-safe building was created, where health-safe smart buildings integrate various technologies to promote healthy environments, mitigate adverse health outcomes, and enhance safety performance. Defining a health-safe smart building should proceed from the desired benefits and their features, and move step by step, through functions enabling the features of the building, towards technologies required to make the functions and features of smart health-safe building real.

6.2.1 Introduction

There is not a commonly accepted, worldwide definition for smart or intelligent buildings, and the term is used interchangeably with similar concepts such as sustainable and high-performance buildings. Smart buildings are typically viewed from the perspective of energy and working efficiency (Borhani *et al*., 2024)

In the energy focused concept of smart buildings, smart buildings are equipped with computer and communication technology aiming to reduce energy consumption and increase comfort. Smart building technology enables intelligent control of buildings to fulfil occupants' needs, contributing to sustainable buildings through dynamic and highly complex system control. Measurement, regulation, and control systems in smart buildings offer direct savings and reduce energy consumption by regulating heating, cooling, ventilation, and lighting.

The European Union (EU) defines smart buildings based on the proposed revisions to the Energy Performance of Buildings Directive (EPBD) and the Smart Readiness Indicator (SRI) concept by saying that “The ‘smartness’ of a building refers to its ability to sense, interpret, communicate and actively respond in an efficient manner to changing conditions in relation to the operation of technical building systems, the external environment (including energy grids)demands from building occupants.” (European Commission, 2018) The SRI concept was developed to assess a building’s ability to adapt to advanced technologies. The SRI rates the smart readiness of buildings in their capability to perform three key functionalities: 1. optimise energy efficiency and overall in-use performance, 2. adapt their operation to the needs of the occupant, and 3. adapt to signals from the grid (for example energy flexibility) (*ibid.*) When defining the SRI, the impact level of functional services produced by the building's technical systems is examined by certain fields of impact that go beyond energy efficiency including also subjects such as convenience, comfort, health and wellbeing, information to occupants, maintenance and fault protection (European Commission, 2020).

The SRI concept is becoming a broadly used standard practice in Europe withing the forthcoming years, but it is not the only relevant approach to smart buildings. Another relevant approach has been proposed by Al Dakheed *et al.* (2020), where smart buildings concept is based on four main features that they have: 1. The ability to react to external influences, 2. The ability to react to signals coming from the network, 3. The ability to interact with the user, and 4. The ability to monitor the building's technical systems and user behavior in real time. (The features reformulated by the authors but keeping the original idea.)

Buildings' ability to react to external influences means that the building must recognize the actual and expected climatic conditions and adapt to them in the best possible way. The building must be capable of minimizing energy use and self-production of renewables. The development of technology has made it possible, for example, to use weather forecasts to control building technical systems. Buildings' ability to react to signals coming from the network means that they must respond to signals from the energy distribution network, the purpose of which is to maximize the efficiency of energy use on the scale of the city (or other community entity). Buildings' ability to interact with the user calls for real-time interaction between user and technology. With the help of the energy management system, it is possible for the user to define usage schedules and setting values that affect comfort. Buildings' ability to monitor its technical systems and user behavior in real time facilitates the realization of features 1-3 and enables, for example, proactive maintenance, real-time identification of faults and identification of other unexpected functions. (Al Dakheed *et al*., 2020)

In this paper we present a concept of smart health-safe building, where health-safe smart buildings integrate various technologies to promote healthy environments, mitigate adverse health outcomes, and enhance safety performance. The concept of smart health-safe building is built on the smart building concept of Al Dakheed *et al.* (2020) by defining benefits that are wanted to be achieved and their features, and move step by step, through functions enabling the features of the building, towards technologies required to make the functions and features of smart health-safe building real. The concept of SRI was presented above because it will offer a common framework under which health-safety aspects of building can be presented.

6.2.2 Method

The used approach to health-safe smart buildings was, at first, to considered desired benefits and then to reflect the benefits in respect to the general four features of smart buildings. The next step was to consider what kind of functionalities a building should have to achieve the four main features of health-safe smart building, and, finally, technologies enabling the functions. All that was done in a series of workshops with researchers as well as industry experts working in the E3 project. The research and industry expert groups were multidisciplinary including expertise in the fields of medicine, virology, ventilation and air purification technologies, building automation, user experience, etc.

Participants brought their special expertise to the research. Each workshop focused on 1-2 steps and the results of a previous workshop were validated in the next workshop. Both physical and virtual workshops were hold.

6.2.3 Results

At first, desired benefits of health-safe smart building were defined. They were formulated as: 1. Lower the risk of contracting an infectious disease, and 2. Chains of infection are broken more quickly. Defining of health-safe smart building then proceeded from the desired benefits step by step towards the necessary technology, like presented in Fig. 1.

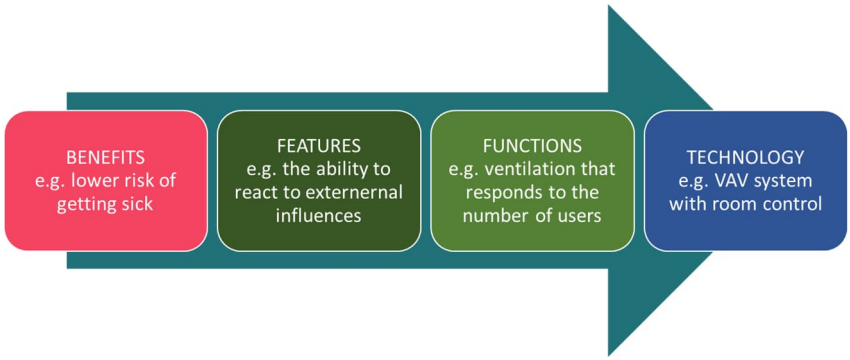

Figure 1. Steps in defining health-safe smart building

Secondly, the four general main features of smart buildings were specified for health-safe smart buildings. The features were formulated as: 1. Building's ability to minimize the spread of infectious diseases, 2. Building's ability to respond, for example, to restrictions on the number of users set by the authorities, 3. Building's ability to provide and receive information from users, 4. Building's ability to offer the previous three key features (Fig. 2). All these features are required in order the desired benefits of health-safe smart building to be fulfilled. Shortages in one or more features will not destroy the concept of health-safe smart building, but shortages will have a negative impact of how well the desired benefits will be obtained.

One may argue that building's ability to provide and receive information from users plays more important role in health-safe than in energy-efficient smart buildings. This is because the concept of health-safe smart building is related to people inside the building and their interaction rather than just the properties of the building.

Figure 2. Main features of health-safe smart building

Thirdly, functionalities related to each of the four main features were defined. In Tables 1-4 they are presented together with examples of technologies enabling the functionalities.

Table 1. Functionality related to the **ability to react to external influences**, and examples of the technology to achieve such functions

Function	**Examples of technology**
User-responsive ventilation	- Variable Air Volume (VAV) System with demand-based control (indoor air quality and infection risk) - Air Purifiers as Part of Ventilation and controlled by building automation system
Contactless functions and clean surfaces	- Automatic water taps - Automated doors - UV light - Easy-to-clean material choices
Spacious spaces and passageways	- Open spaces and flow control with the help of spaces (architectural choices) - Access control system and people flow management systems

Table 2. Functionality related to the **ability react to signals coming from the network** and examples of the technology to achieve such functions

Function	**Examples of technology**
Possibility to limit the number of visitors or building users	- Access control system and people flow management systems - People counting sensors
Providing information about visitors	- Utilization monitoring and control system
Spacious spaces and passageways	- Architectural solutions - Automated doors - Access control system and people flow management systems

Table 3. Functionality related to the **ability to interact with users** and examples of the technology to achieve such functions

Function	**Examples of technology**
Users can influence indoor conditions	- VAV system integrated into the building automation system (BAS) - Personal ventilation at workplaces and air curtains
Provides users with information about congestion and the possibility to minimize time spend in the building	- Mobile applications providing real time information about infection risk and waiting times
Visible conditions and clean surfaces	- Interactive room sensors - Architectural solutions and easy-to-clean material choices

Table 4. Functionality related to the **ability to monitor building´s technical systems and user behavior in real time** and examples of the technology to achieve such functions

Function	**Examples of technology**
Monitoring and forecasting the use of space	- Utilization rate and fill rate sensors (smart room sensors) - Character recognition with cameras
Assessment of infection risk	- Infection risk calculation tool/application
Automatic fault detection	- AI based fault detection integrated to building automation system - Airflow measurements integrated to building automation system

The benefits, features, functions and technologies are summarized in Fig. 3 as a concept of health-safe smart building.

The presented concept of health-safe smart building takes into account various infection routes. Some pathogens spread mainly through air transmission, while some others through direct contacts with surfaces. The infection route will have an impact to the importance of specific technologies used in the mitigation of the spread of pathogens. For example, ventilation and the production of clean air play a significant role in the fight against diseases that spreads through air transmission of pathogens. On the other hand, automated water taps and doors as well as disinfection technologies, such UV light solutions may play an important role in the mitigation of the spread of pathogens through direct contact.

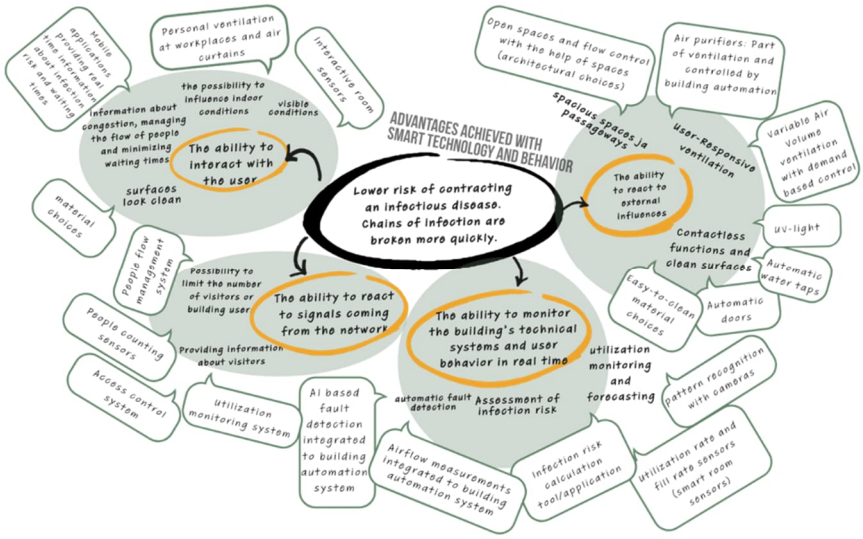

Figure 3. Concept of health-safe smart building

It is important to recognize that building's health safety and energy efficiency must not conflict with each other. At its best, a smart building produces a safe environment while operating in an energy-efficient manner. One may even argue that any solution that is not energy efficient is not smart and it is unlike that it will be implemented.

Some technical solutions mentioned above may allow identification and monitoring of people. When such technologies are used, it is highly important that information security as well as ethical and other regulative aspects must be considered when using technology to identify and monitor people.

6.2.4 Discussion

The Smart Readiness Indicator (SRI) concept is becoming increasingly important in the context of (smart) buildings. In the SRI calculations, human well-being and health is currently mainly examined through comfort and the effects of pollutants coming from the building and how the IAQ conditions affect a person's health (European Commission, 2020).

We argue that, in the future, the prevention of diseases that spread from person to person should be better considered in the SRI calculations. The concept of health-safe smart building could help in the improvement of SRI calculation when one wants to include aspects of preventing the spread of infectious diseases into the calculation. It gives an idea of additional services related to the prevention of infectious diseases. We have spoken above about technologies, but it is important to recognize that, in addition to technical systems, spatial planning and architectural

solutions can also have a great impact on building's health safety and smart readiness.

6.2.5 Conclusions

A concept of health-safe smart buildings was created that goes beyond the traditional energy-efficiency focused concept of smart building to integrate various technologies to promote healthy environments, mitigate adverse health outcomes, and enhance safety performance. As the concept is related to people inside the building and their interaction rather than just the properties of the building, building's ability to interact with its users is a highly important feature of health-safe smart building.

6.2.6 Acknowledgements

We would like to thank the researchers and experts that participated into the workshops where the concept was elaborated for their contribution to the results.

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6.3 Human Factors in the Design of Solutions Mitigating the Spread of Pathogens

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Abstract: Design principles related to human factors and user acceptance for the development of solutions mitigating the spread of pandemic/epidemic in indoor spaces were developed. The design principles were given as User Experience (UX) Vision and Goals together with context-dependent specifications, the UX Goals and specifications concretizing the Vision. The E3 UX vision was formulated as 'Breathe, Focus, Thrive: Building a Foundation of Health Safety and Wellbeing'.

6.3.1 Introduction

When designing solutions mitigating the spread of pathogens, it is not enough to take into account input from natural sciences and technology. To be accepted by the users, the design of solutions should consider also human factors related to the use as well as business perspectives. This paper focuses on the research done on human factors in the E3 project.

The human factors research of E3 project aimed to give design principles related to human and organizational behaviour, user experience, and acceptance for the development of solutions mitigating the spread of pandemic/epidemic in indoor spaces with a special focus on air borne infections. The design principles arise from the understanding of the use of target spaces, and they are given as User Experience (UX) Vision and Goals together with context-dependent specifications. The goals aim to take into account relevant target and stakeholder groups of solutions. Three contexts were considered: hospitals, day care centres, and offices.

User experience and its improvement have been for long an important part of the development of devices and services in the consumer business (Hartson and Pyla, 2012, Hassenzahl and Tractinsky, 2006). During the last 10-20 years it has become more and more important also in industrial products and services in business-to-business markets. In work contexts, user experience refers to the way a person feels about using a product, service or system and how this shapes the image of oneself as a professional (Roto et al. 2012; Nuutinen and Koskinen 2015). For example, in the case of a solution that works well, and is appreciated in working society, the user of the solution can feel joy, because the working is fluent, and proud because he or she has the right to use the solution.

With experience design, you can facilitate a certain kind of experience that you would like the users to have. Still, it is important to understand that it is not possible to design a given user experience. The experience is a result that is affected by several factors, including the features of the particular solution,

previous experiences of the user with similar solutions, and experiences of others. With the help of experience design, however, it is possible to increase the probability of certain kinds of user experience. To gain this, one must put efforts into UX design and be systematic throughout the product development from ideation until the implementation of the solution. UX vision and UX goals can guide the design process by giving specific guidelines for the work. A UX vision reflects the overall experience that is aimed to be facilitated for the users of the solution. UX goals aim to concretize the UX vision through an emphatic understanding of what users want to achieve in their work, and how this could be best supported with a thorough understanding of what users want to achieve in their work, and how this could be best supported. Thus, it is important to consider the role of solution within the work context in the core tasks of work.

6.3.2 Methods

The typical approach to user experience uses either of two design principles - experience or problem-driven – or both of them. The experience-driven design is about crafting positive user interactions. It starts with delving into fundamental human needs and the uplifting moments in life, leveraging these insights to conceive new products that foster such desired experiences. The problem-driven design centres on grasping users' challenges and pain points. In the E3 project, the typical approach is supplemented by the human factors approach that offers a comprehensive outlook encompassing broader contexts and user objectives within larger systems (such as hospitals, day care centres, and offices), informed by user research.

The research applied the methodology of the abductive case study. Empirical data was collected through interviews of personnel in one hospital department and in two day cares that were under interventions where air purifies were installed into the rooms in order to clean the air from pathogens and other impurities in the air. Personnel interviews were done both prior to and during the interventions. In the interviews before intervention, the aim was to gain an understanding on working practices, status, and expectations towards the intervention. Interviews during the intervention focused on the experiences of personnel. Empirical data was supplemented by human factor-related findings of Covid-19 reported in literature and the internet as well as by material from discussions done within the E3 project with several stakeholders, including owners and users of office and other public premises. The data was analysed using the phased analysis approach by the authors together with reflections from other research and industry experts of E3 project. The reflections were gathered in two physical and one virtual workshop.

In general, the following starting points should be used when creating UX vision and goals. The list is based on research done in the UXUS-programme (Nuutinen and Koskinen, 2015), but the formulation is an outcome of the E3 project:

1. Brand – Positive things where the brand or company is known.

2. Theory – Scientific understanding on human and organizational behaviour.
3. Empathy – Emphatic understanding on the environment of users and the needs and feelings of users in the environment.
4. Technology – Factors related to the used specific technologies that may have positive or negative impact to user experience.
5. Purpose – What is the purpose of solution.

In the creation of the E3 UX vision and goals, less attention was paid to (1) brand and (4) technology as the target was to create a generic vision and goals applicable to all stakeholders of the E3 project. Accordingly, some customization may be needed when applying the results into company specific UX design work.

6.3.3 Results

The analysis of collected data resulted in the following **E3 UX Vision** for the overall experience that we want to facilitate for the users of E3 solutions in hospital, day care, or office contexts for the mitigation of the spread of pathogens:

Breathe, Focus, Thrive:
Building a Foundation of Health Safety and Wellbeing

The first part of the vision, 'Breathe, Focus and Thrive', reflects the experience of end users in health safe indoor environment allowing them to do their main functions of work with success. The second part of the vision, 'Building a Foundation of Health Safety and Wellbeing', reflects the experience of designers and solution providers enabling health safe indoor environments, where the providers can be understood to also include employers and facility owners. Thus, the vision integrates the users with the solution designers and providers, workers and facility owners and employers.

The **E3 UX Goals** concretizing the UX vision were formulated into the following form:

The solution should aim to provide users with an experience that:

- **Supports essential in work**
- **Promotes being together safely**
- **Respects personal health and safety needs discreetly**
- **Justifies feelings of safety**
- **Ensures user acceptance as a part of the whole**

The E3 UX Goals were formulated in a generic way so that different companies could apply them in the design and implementation work of various solutions mitigating the spread of pathogens in indoor environments. When applying them in the UX design work of a company, these human factor-related experience goals may need to be supplemented by a brand-related experience goal and a technology-related experience goal.

The last two goals 'Justifies feelings of safety' and 'Ensures user acceptance as a part of the whole' assume that the users have research-based information available on the principle, impact mechanisms and right use of the solution. The fact that the solution may not have a principal role in their work could make it challenging to communicate all necessary information to the users of the solution. Not all users are interested in the solution. Also, the context (hospital, day care, office, etc.) will define how the information should be communicated. The context also has an impact on the first three goals. Therefore, context-dependent specifications will be needed to further concretize the generic E3 UX Goals.

The context-dependent specifications of E3 UX Goals were largely based on personnel interviews in hospital and day care contexts as well as discussions with office stakeholders. In the hospital context, it is important to communicate the benefits of solutions to personnel, i.e. how their use can mitigate the air transmission of pathogens. As the solutions, such as air purifiers, have the role of supplementary, not primary instruments in medical care, the positioning of devices should be designed so that they do not alter by any means the medical or nursery operations in the room in question. On the other hand, the outlook of devices has less importance in hospitals than in other environments. These are examples of context-dependent specifications of UX goals for hospitals. A more complete set of specifications is given in Table 1.

In the day care context, attention should be paid to involving personnel of day care centres, and to some extent also children, to the design and start-up of solutions. Acceptance of new solutions will be much easier when the people in the day care have participated in the design and start-up work. The noise of devices may be an issue in day cares. When adjusting the noise, it is important to communicate that decreasing the noise may weaken the performance of device. In day care centres, the outlook of solutions is much more important than in hospitals, but like in hospitals, the positioning of devices should consider the purpose of the room. In day care centres, the floor area should be maximised for the use of children. There is also a need to have clear visibility in the room. Thus, other solutions than those standing on the floor should be preferred. These are examples of context-dependent specifications of UX goals for day care centres. A more complete set of specifications is given in Table 2.

Table 1. Viewpoints for the use of UX Goals in the context of hospitals

UX Goals **The solution should aim to provide users with an experience that:**	**Specifications in a hospital context**
Supports essential in work	-Position the devices by taking into account the purpose of the room, note also that there may occur a need to slightly rearrange the devices due to medical or nursery operations
Promotes being together safely	-Safe working and staying in the patient and waiting rooms
Respects personal health and safety needs discreetly	-Acceptable noise (in the night time) -Otherwise less important goal in the hospital context
Justifies feelings of safety	-Bring solutions and their benefits into the guides and practices of the department/hospital
Ensures user acceptance as a part of the whole	-Give understanding to the personnel on the impact of solution into the mitigation of pathogen spread as a part of the whole -Educate the use/control of the device for personnel that should handle that

In the office context, special characteristics are the high need for flexibility and shareability in the use of workspaces. The solution should allow activity-based workspaces. Secondly, personal health and safety needs are very important. Some office workers prefer healthier and safer conditions than others. The conditions may include indoor air quality, temperature comfort, sound, outlook etc. The needs of these people should be respected discreetly. The solutions should increase attraction to come into the office. At the beginning of the E3 project, we had a vision to have an application that would give real-time information on health-safety of space, or indoor air quality, but that vision did not come true. If someday realised that would promote justified feelings of safety in meeting rooms etc. These are examples of context-dependent specifications of UX goals for offices. A more complete set of specifications is given in Table 3.

Table 2. Viewpoints for the use of UX Goals in the context of day care centres

UX Goals **The solution should aim to provide users with an experience that:**	**Specifications in day care centre context**
Supports essential in work	- Position and select the devices by taking into account the need to maximise floor area for the use of children and the need to have clear visibility in the room -Adjust the noise to an acceptable level. When adjusting, remember to communicate that decreasing the noise may weaken the performance.
Promotes being together safely	-Allowing health-safe small group activities
Respects personal health and safety needs discreetly	-Joint design with end-users (including the look of devices) and start-up situation -Take into account highly sensitive persons (sounds, smell, outlook etc.)
Justifies feelings of safety	-Give research-based information on the benefits of the solution in a form that can be understood by the end-users
Ensures user acceptance as a part of the whole	-Give understanding & argumentation for the personnel on the impact of solution for the improvement in conditions and health-safety

The E3 UX Vision and Goals are to guide the design of solutions mitigating the spread of pandemic/epidemic in indoor spaces by taking into account principles related to human factors and user acceptance. The goals and their context dependent specification also give guidance for the communication to users of solutions. To summarize three key points related to communication, we can say that: 1. Describe the purpose of use through a positive message. For example, an air purifier purifies indoor air from impurities and fine particles and, in this way, increases the health-safety of the space. (The point relates to the UX goal 'Promotes being together safely'.) 2. Explain the operational principle of the solution. For example, the device purifies the air by drawing dirty air through its filters and blowing clear air out after the filtration. (Justifies feelings of safety) 3. Tell essential facts affecting the user experience. For example, the degree of air

purification is related to the power of the device. Higher power means better purification but also higher noise and air current, and vice versa. (Respects personal health and safety needs discreetly)

Table 3. Viewpoints for the use of UX Goals in the context of offices

UX Goals **The solution should aim to provide users with an experience that:**	**Specifications in office context**
Supports essential in work	The solution(s) should -bring attraction for coming into the office (especially during epidemics) -allow activity-based workspaces (use of rooms as flexible and shareable spaces) -support the brand of the office/company
Promotes being together safely	-Allowing health-safe co-working in meeting rooms and open-plan offices
Respects personal health and safety needs discreetly	-Allow personal control to desktop devices. Automated control of the room. -Adjust the noise to an acceptable level -Pay attention to temperature comfort (that may be highly person dependent)
Justifies feelings of safety	-Give information on the benefits of the solution to allow efficient use of the solution -Option: Give real-time information on health safety of space e.g. through an application
Ensures user acceptance as a part of the whole	-Give an understanding on the impact of the solution on the mitigation of pathogen spread as a part of the whole (including instructions for cleaning)

6.3.4 Discussion and concluding remarks

A journey towards desired user experience through E3 UX Vision and Goals is not only about the design of products, services, and indoor environments. It is also

about shaping interaction between people in case of future epidemics or pandemics. Designers and developers of technology can affect how people can survive in good health through such times. Implementing the design principles presented in this paper, the designers and developers can promote how users of the solutions could do their daily work with success, enable safe being together, and, ultimately, the creation of a more health safe society than today.

The core of UX design goes beyond aesthetic character and functionality towards empathy, understanding and commitment to improving the environment of users (people). Thus, UX design is more than a process. A deep understanding of the world of users through UX Vision and Goals will facilitate innovation of improved or totally new solutions.

As a final note, the study has, in line with the E3 project, focused on cases where air transmission is the principal route for the spread of pathogens. Accordingly, air purifiers have been addressed as technological solutions. While the presented UX Goals may be general, context dependent specifications for their use should be revised when the principal transmission route of pathogens is through direct contact.

6.3.5 Acknowledgements

We thank City of Helsinki and the personnel of two day care units of Helsinki as well as HUS and the personnel of one hospital department of HUS for their contribution for the interview part of the study.

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6.4 Assessing the Value Indoor Environmental Quality Creates in the Real Estate Sector – Office occupants' Perspectives

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Abstract: This study aimed to assess the perceived value of indoor environmental quality for office occupants, and their willingness to pay (WTP) for a high-quality indoor environmental product. The research was conducted as a mixed-method study, combining 24 thematic interviews and a survey with 46 usable responses. The interviews, which included real estate owners, consultants, and office experts such as property managers, served as the basis for the survey. The survey was directed at office experts. The findings revealed that office occupants in Finland are willing to pay for a high-quality indoor environmental product, with a median WTP of 0,24 €/m² per month.

6.4.1 Introduction

In recent decades, organizations have shown growing interest in healthy office environments. The World Health Organization (WHO) defines health as a state of complete physical, mental and social welfare, not just the absence of infirmity or disease. Therefore, a healthy office should support the overall health and well-being of its occupants and prevent negative health impacts. (Buskermolen et al. 2021) One of the most critical factors in creating a healthy office space is a high-quality indoor environment. Indoor environmental quality (IEQ) is defined as consisting of five elements, which are indoor air quality, thermal comfort, acoustic comfort, visual comfort, and virus control. (Kakoulli et al. 2022)

Research shows that high-quality and healthy offices can reduce employee absenteeism by mitigating health risks, such as uncomfortable temperatures, poor air quality, or exposure to viruses. These office environments also improve employee health, satisfaction, and well-being, leading to higher productivity, better employee engagement, and overall organizational effectiveness. (Buskermolen et al. 2021) Healthy office spaces also support broader corporate goals, such as corporate social responsibility (Parker 2020).

The growing demand for healthier office spaces offers an opportunity for real estate owners and landlords. By providing healthy offices, they could reduce vacancy rates, retain tenants, and, for example, charge higher rents. However, it remains uncertain, whether tenants are willing to pay a rent premium for such office spaces. This uncertainty makes it difficult for property owners, investors, and developers to justify the financial viability of offering healthier, more expensive offices. Therefore, as IEQ is a key factor in a healthy office, this research aims to

assess office occupants' perceived value of high-quality indoor environments and their willingness to pay (WTP) for a high-quality indoor environmental product.

6.4.2 Method

The research used a mixed-method approach, combining thematic interviews and a survey. In the summer of 2023, 24 experts were interviewed, including real estate owners, workplace consultants, and office space occupants. The interviews focused on assessing the value of IEQ for office users.

Based on the interviews, a survey was developed to assess office occupants' WTP for a high-quality indoor environmental product. The online survey was conducted over two months, from early June to late July 2024. The questionnaire was carried out using the SurveyMonkey platform. The survey was distributed via a property owner, which made it impossible to accurately determine the response rate. The survey received 46 usable responses (Table 1).

Table 8. Respondent categorization (total n=46)

	n	Percent
Sector		
Information and communication	13	28
Wholesale and retail trade	7	15
Professional, scientific, and technical activities	6	13
Real estate and construction	5	11
Financial and insurance activities	4	9
Manufacturing	3	7
Public administration and defense	3	7
Other	5	10
Size – employees		
Micro – under 10	5	11
Small – under 50	16	35
Medium – 50–249	7	15
Large – over 250	18	39
Respondent's main place of work		
Helsinki	33	72
Espoo	8	17
Tampere	4	9
Oulu	1	2

The respondents represented a total of 13 different sectors. The most common sector was information and communication (28 %), followed by wholesale and retail trade (15 %), and professional, scientific, and technical activities (13 %). The professional, scientific, and technical activities sector included, for example, law firms. Most organizations were large operators (39 %), with more than 250

employees or small operators (35 %), with more than 10 but less than 50 employees. Additionally, most respondents' main place of work was in the capital region, in Helsinki (72 %) or in Espoo (17 %).

6.4.3 Results

This research evaluated office occupants' perceived value of IEQ through interviews and their willingness to pay for a high-quality indoor environmental product through a survey.

Interview results

The interviews offered valuable insights into how office occupants perceive the value of IEQ. The COVID-19 pandemic permanently altered work habits, leading organizations to focus on supporting the future of work. Especially with the increase in remote work, organizations' priorities shifted towards encouraging employees to return to the offices, enhancing employee engagement, and improving employee well-being. At the same time, organizations also prioritized productivity, efficiency, and increasingly, sustainability. The quality of office spaces, including indoor environmental conditions, was considered important in supporting these objectives.

In summary, organizations viewed IEQ as important for promoting employee well-being and satisfaction. As its significance continues to rise, the demand for IEQ solutions in the office market is also likely to increase in the future.

Survey results

The survey provided key insights into office users' willingness to pay for a high-quality indoor environmental product, as well as their preferences for purchasing methods of IEQ solutions. The respondents assessed the attractiveness of products and services that improve offices' IEQ on a Likert scale from 1 to 7, with 'strongly not interesting' corresponding to 1 and 'very interesting' to 7. The majority of the respondents indicated a level of interest, as 71 % considered these solutions as very interesting, interesting, or somewhat interesting (Figure 1).

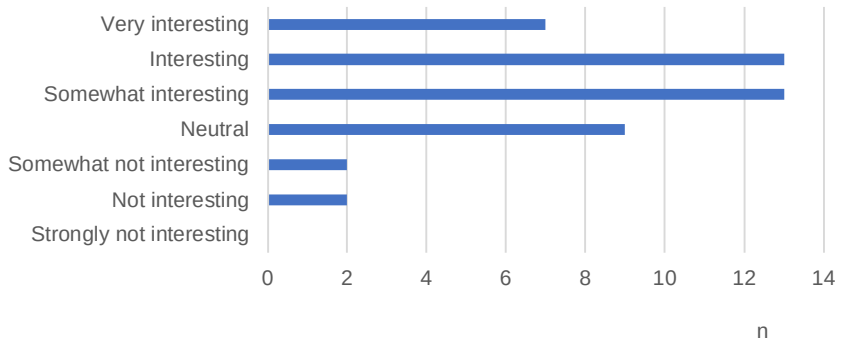

Figure 22. Interest in products and services for improving IEQ (total n=46)

After assessing the overall interest, respondents were also asked how they preferred to purchase IEQ products and services. Most respondents preferred purchasing these solutions through a property owner's or landlord's leasing model (figure 2). However, seven respondents were not interested in buying such solutions. Additionally, two respondents chose the 'other' option, with one finding all methods equally preferable and the other suggesting that buildings should be equipped with interfaces during construction phase to transfer and enrich data later.

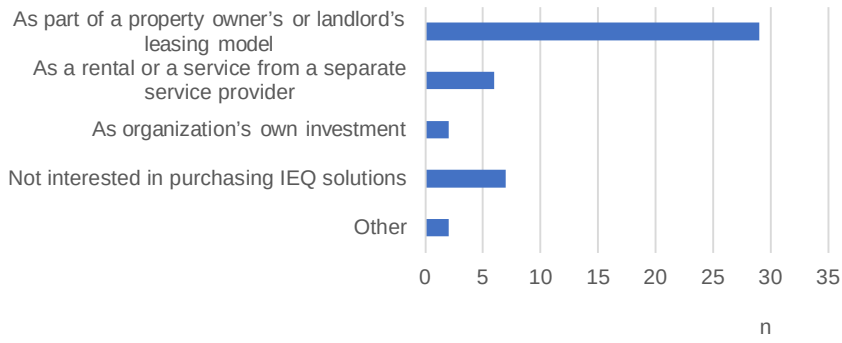

Figure 23. The preferred method to purchase IEQ solutions (total n=46)

The respondents were asked about their interest in purchasing IEQ products and services. Of the 46 respondents, 39 expressed interest in purchasing IEQ products. These individuals were then asked to assess their monthly WTP for a comprehensive IEQ solution. Excluding two respondents who were unsure of their WTP, the sample size was 37.

The respondents' monthly WTP was analysed by calculating the mean and median values (table 2). The overall mean WTP was 0,94 €/m^2 per month, while the median was 0,24 €/m^2 per month. The difference between these values suggests that a few higher WTP responses are raising the average. Therefore, the median can be considered a more accurate representation of overall WTP.

Table 9. The average and median values of respondents' monthly willingness to pay

Total of office spaces	n	WTP mean (€/m^2)	WTP median (€/m^2)
Under 300	11	1,86	0,25
300-5000	14	0,88	0,67
Over 5000	12	0,15	0,12
Total	37	0,94	0,24

Smaller organizations had the highest average WTP but a much lower median. This indicates that a few respondents were willing to pay significantly more, while most had lower WTP values. Those willing to pay significantly more were dissatisfied with their offices' IEQ conditions, as well as their monitoring, data availability, and controllability, despite considering these factors important.

The average and median WTP values for medium-sized and large organizations were relatively similar. This indicates that there was less variation and more consistency in their WTP for the IEQ solution.

In summary, the overall median WTP was 0,24 €/m² per month, with variations observed across organization size and sectors. However, it is important to note that the sample sizes were relatively small.

6.4.4 Conclusion

Interest in healthy offices and high-quality indoor environments has grown among organizations in recent decades. Despite this growing interest, property owners and investors remain cautious due to uncertainty over tenants' willingness to pay for such office spaces. This research found that high-quality indoor environments provide significant value not only for office users but also for property owners, landlords, and investors. Office users and employers benefit from IEQ solutions in several ways, including improved employee health and well-being, enhanced productivity, increased revenues, and a strengthened commitment to corporate social responsibility. Similarly, these products offer value to investors, property owners, and landlords by improving tenant satisfaction, increasing occupancy rates, enhancing corporate social responsibility, and raising the value of real estate assets.

In general, occupants expressed strong interest in acquiring solutions that improve the IEQ of their workspaces, with many demonstrating a willingness to

pay for high-quality indoor environmental products. The occupants showed a median WTP of 0,24 €/m² per month, although this amount varied among individuals. Preferences for acquiring these solutions varied as well. Most preferred to access these solutions through leasing models provided by property owners or landlords. However, there was also some interest in renting or purchasing the solutions as part of their own investment.

In summary, occupants are generally interested and willing to pay for solutions improving offices' IEQ, but most prefer not to manage the purchasing process themselves. Instead, they prefer property owners and landlords to incorporate these solutions into their services

6.4.5 Acknowledgements

We would like to thank all the experts who participated in the interviews and the survey. We would also like to thank all the experts who contributed to the development and distribution of the survey.

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6.5 Adoption of IEQ Innovations in the Real Estate Sector – Innovation Developers' Perspectives

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Abstract: This study aimed to identify the key barriers and drivers within the real estate industry that influence the diffusion of innovations improving indoor environmental quality (IEQ). The research also explored opportunities for promoting the adoption of these solutions. The study was conducted as a qualitative thematic interview study and the data consisted of 15 interviews. The interviewees were experts specializing in developing solutions aimed at enhancing the IEQ of buildings and premises. As a result, seven key factors influencing the diffusion of IEQ innovations in the real estate sector were identified. The identified factors included megatrends and transformative trends, cultural differences, regulation, real estate industry's established practices, lack of collaboration and trust, innovations' complexity, and stakeholders' attitudes and expertise. These factors were identified at the macro, meso, and micro levels of the socio-technical model.

6.5.1 Introduction

In late 2019, COVID-19 virus started to spread and escalate into a global pandemic. To mitigate the spread of the virus, widespread restrictions were implemented. The restrictions led to the shutdown of society and the loss of opportunities for in-person human interaction. This rapid change highlighted the importance of indoor environmental quality (IEQ) in ensuring building users' safety and supporting their health and well-being. On the other hand, IEQ has been recognized to impact occupants' productivity and satisfaction. In contrast, for real estate owners and investors, providing a high-quality indoor environment can decrease vacancy rates, lower operating costs, and increase returns on investments. At the same time, employers can benefit from reduced sickness rates, improved productivity, higher employee engagement, and eventually revenue growth. (Borgentorp et al. 2023)

Despite the clear benefits, adoption of IEQ innovations have been rather slow in the real estate sector. Innovation is described as a process of institutionalization, involving the creation of social norms, values, symbols, and rules. While institutional structures impact the diffusion of innovations, innovations can also reshape existing institutional structures. The diffusion of innovation also impacts the development of socio-technical structures. (Vargo et al. 2020)

The socio-technical change model illustrates the effects of innovation on existing socio-technical structures. The model describes the impacts on three levels, which are macro, meso, and micro level. The macro level, or operating

environment, refers to a broader societal operating environment and developments. The meso level refers to the industry level, such as the real estate sector. The micro level focuses on the organizational and individual levels. The socio-technical change model also describes how existing socio-technical structures influence the development and adoption of innovations. Innovations can drive socio-technical changes, but existing socio-technical structures can also hinder innovations and their adoption. (Geels 2004; Vargo et al. 2020; Mantere 2023)

This research aims to identify the key barriers and drivers affecting the diffusion of IEQ innovations in the real estate sector, as well as strategies for promoting the diffusion of these solutions. In this study, IEQ innovations refer to innovations that improve the quality of indoor environments, such as air purifiers, ventilation systems, occupancy data solutions, and other solutions designed to enhance indoor environmental quality and occupant satisfaction.

6.5.2 Method

The research was conducted as a qualitative thematic interview study. The research data consisted of 15 interviews with IEQ solution developers. The backgrounds of the interviewees were diverse, ranging from startups to established operators with a significant presence in international markets. The number of interviewees provided a good representation of IEQ solution developers, increasing the validity of the results.

The research data were collected during the summer of 2022. The interviews were recorded and transcribed into verbatim. The data were analysed by using Atlas.ti data analysis software. During the analysis, the data were systematically categorized into three primary levels – macro, meso, and micro – each representing distinct factors influencing the diffusion of innovation. These categories were further subdivided into two categories, which were barriers and drivers.

6.5.3 Results

This research identified seven key drivers and barriers influencing the diffusion of IEQ innovations in the real estate sector. These factors were identified at the macro, meso, and micro levels of the socio-technical model, representing the broader operating environment, industry, and organizational and individual levels. At the macro level, the identified barriers and drivers include megatrends and transformative trends, and cultural differences (Table 1).

Table 10. Key factors affecting innovation diffusion in the real estate sector at the macro level

Level	Factor influencing innovation diffusion	Impact on adoption of innovation	Solution proposal
Macro	Megatrends and transformative trends	Barrier and driver	• Analysing trends and leveraging them as opportunities. • Designing flexible and scalable solutions that can adapt to changes in the operational environment.
	Cultural differences	Barrier and driver	• Focusing on market research and segmentation to ensure products fit regional needs. • Tailoring marketing strategies to align with local and cultural specifics. • Localizing products to enhance adoption in targeted markets.

Mega and transformative trends, create both pressures and opportunities for innovation. These trends, such as climate change, digitalization, changes in work habits, and the COVID-19 pandemic, reshape the broader operating environment and create uncertainty. As a result, organizations must modify their practices to survive and thrive. The different trends can also quickly impact the adoption of certain innovations. For instance, the COVID-19 pandemic led to increased demand for IEQ solutions, such as air filtration systems. However, while the pandemic accelerated the demand and adoption of some innovations, it also reduced the need for others. For example, as remote work increased and occupancy rates dropped due to the virus, demand for space analytic solutions decreased significantly.

Cultural differences also affect the demand for and adoption of innovations at the macro level. Varying values and traditions shape how different societies perceive and respond to new technologies. For example, demand for advanced ventilation systems was higher in the Nordic countries than in Central and Southern Europe, where common practices like opening windows were considered sufficient for ventilation. Some societies also embrace change more readily, while others may be slower to adopt new innovations as they favour familiar practices or even resist change. Thus, identifying the right market is crucial, because regional differences in demand for new solutions, such as IEQ innovations, can be significant.

The macro level developments not only reshape the broader operating environment but also drive, for example, regulatory responses at the meso level. At the meso level, barriers and drivers of innovation diffusion also include the real

estate industry's established practices and a lack of collaboration and trust (Table 2).

Table 11. Key factors affecting innovation diffusion in the real estate sector at the meso level

Level	Factor influencing innovation diffusion	Impact on adoption of innovation	Solution proposal
Meso	Regulation	Barrier and driver	• Actively collaborating with legislators and authorities and engaging in lobbying and information sharing to promote innovation-friendly regulations. • Anticipating future legislation and designing products flexible enough to adapt to changes.
	Real estate industry's established practices	Barrier	• Improving communication and promoting co-creation. • Creating pilot projects to showcase the effectiveness of new solutions.
	Lack of collaboration and trust	Barrier	• Building long-term relationships and partnerships with customers to foster trust. • Transparent communication and co-creation with stakeholders throughout the innovation process will help build a foundation of collaboration, which is crucial for introducing new solutions.

Regulations, such as laws and guidelines, can either promote or hinder the diffusion of innovations. The real estate sector is often seen as traditional and resistant to change, so mandatory rules can sometimes be necessary to drive organizations to adopt new technologies and modify their practices. However, outdated regulations can hinder innovation by making it difficult or even impossible to implement new solutions. There is a strong need for more proactive regulation in the real estate sector to better support innovation and increase adoption of new technologies. For example, the adoption of IEQ innovations could be accelerated by implementing regulations that promote healthier indoor environments and encourage the use of advanced IEQ solutions.

At the meso level, industries' established practices influence the diffusion of innovations in a similar way as cultural differences at the macro level. The real estate sector is characterized by features such as cost-centricity, setting high and precise requirements in procurement documents, inadequate communication, and

limited co-creation and co-innovation. These established practices leave little room for risk-taking and experimentation with new solutions. For instance, procurement documents for IEQ solutions may impose requirements that are difficult or even impossible to meet. Therefore, adequate solutions may be excluded from tender processes, and introducing new solutions to the market can become more difficult. The challenges related to procurement can be seen as closely linked to other meso-level barriers, as well as micro-level issues, such as the complexity of innovations and the customers' lack of expertise (Table 3).

Table 12. Key factors affecting innovation diffusion in the real estate sector at the micro level

Level	Factor influencing innovation diffusion	Impact on adoption of innovation	Solution proposal
Micro	Innovations' complexity	Barrier	• Offering comprehensive solutions with adequate training and support during implementation. • Clear communication and user-friendly interfaces. • Providing practical guides to support the use and adoption of innovations.
	Stakeholders' attitudes and expertise	Barrier and driver	• Increasing stakeholders' understanding and expertise through training and workshops. • Engaging stakeholders early in the innovation process to build acceptance. • Clearly communicating business benefits to shift attitudes toward new technologies.

IEQ solutions can be seen as complex, due to their multifactorial nature. Thus, customers may have limited experience with the solutions' principles and objectives. As a result, they may not fully understand the features and benefits of the solutions, leading to unrealistic procurement requirements. However, effective collaboration and clear communication about the benefits of IEQ solutions were identified as drivers of the innovations' diffusion. By providing well-researched information to the customers, they can make more informed decisions and set realistic requirements. Building trust-based relationships with customers also makes it easier to encourage them to try and pilot new solutions.

6.5.4 Conclusion

High-quality indoor environments have been proven to offer benefits for occupants, employers, property owners, and investors. Despite this, the diffusion of IEQ innovations in the real estate sector has been relatively slow. This research identified a total of seven key drivers and barriers influencing the diffusion of IEQ innovations in the real estate sector. These factors were identified at the macro, meso, and micro levels.

One of the main barriers identified was the combination of inadequate marketing and the complexity of the IEQ innovations. The complexity of these solutions often made it difficult for potential customers to fully understand their technical features and benefits. As a result, customers were hesitant to adopt existing solutions, pursued solutions that did not exist, and set unrealistic demands in procurement documents. Thus, enhancing potential customers' knowledge through clear communication and research-based evidence is critical for promoting the adoption of IEQ innovations. Also, offering more comprehensive solutions, or turnkey solutions, can help potential customers better understand the solutions' benefits, reduce their workload, and simplify the decision-making process for adopting new innovations. This approach may require collaboration between solution developers to create integrated offerings. Adoption can also be further driven by the development of new guidelines and the implementation of mandatory legislation. Furthermore, innovation developers should anticipate and analyse trends to identify new opportunities, but also design flexible, scalable solutions that can adapt to changing operational environments.

In summary, a multi-faceted approach is needed to promote the adoption of IEQ innovations. This includes effective market research and marketing, and well-designed service solutions that meet customers' needs, along with efforts to develop new guidelines and integrate regulations into legislation to further support the adoption.

6.5.5 Acknowledgements

We would like to thank the experts that participated into the interviews.

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7 Controlled micro-environments

7.1 Controlled micro-environments for locally improving indoor air quality

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Abstract: This paper introduces the concept of controlled micro-environments for locally improving indoor air quality. The concept was under special consideration in the E3 Pandemic Response project, the research including both experiments and simulations.

7.1.1 Introduction

It is well known that ventilation improves the indoor air quality of room, and that the increase of airflow rate makes the ventilation more effective. It is also known that transmission route of many pathogens causing infectious diseases take place through aerosols and adhesion of aerosols into particles in the air. Rooms could, thus, be made safer against pathogen flow by increasing ventilation rate but that could increase energy costs and affect thermal comfort of people inside the room.

During the E3 project an idea was arisen to create special zones inside the room with increased air quality and decreased infection risk. Such zones would locate there where people typically spend their time, for example at their working desks. Measures to improve the air quality would not be addressed to the entire room but focused on these special zones. By this way the costs of air quality improvements would become moderate, but at the same time the morbidity and duvet days of the people may stay low even during epidemic.

The zones could be called as controlled micro-environments. Accordingly, we formulated a research question for the study: **How much the air quality could be improved with controlled micro-environment solutions?** The air quality improvement was considered as the decrease of exposure to infectious aerosols

in respect to cases without any specific measures aiming to locally improve the air quality, that is, general ventilation only.

Our initial plan was to study, at first, alternative approaches to create controlled micro-environments in a laboratory and, after that, to make an intervention, like that described in Chapter 9 for day cares, in real office environments. Unfortunately, it became obvious that the duration of project was not long enough to have both the laboratory study and the followed intervention in offices in a way to have statistically validated results on the impact of controlled micro-environment on the health of office workers measured as the decrease of duvet days. Therefore, the E3 research of controlled micro-environments focused on laboratory experiments and CFD simulations.

This paper introduces the subject and closes the conclusions of the study by discussing on the practical implications of the study. Experimental arrangements used in the laboratory measurements are presented in the subsequent paper of the chapter, followed by papers on key experimental findings and key findings from simulations.

7.1.2 Controlled micro-environments

The most used ventilation method of air distribution in many types of buildings is mixing ventilation where contaminants of room air have been diluted in room air with fresh ventilation air. This can be done with different types of supply air diffusers with the target to mix the room air efficiently. The most common type is a radial ceiling diffuser supplying ventilation air radially along the ceiling surface with high velocity. This was selected as the main reference case in E3 research of controlled micro-environments.

Another common air distribution method is displacement ventilation, which has been utilised especially for high or large rooms where fresh ventilation air has been supplied directly to the occupied zone and room air is exhausted from ceiling level. This enables convective flow from heat sources to slowly carry cleaner room air from floor level towards ceiling level without mixing it. The most common type of displacement ventilation diffuser is located at the floor level and supplies ventilation air horizontally to the occupied zone with low velocity. That was another reference case in E3 research study focusing on controlled micro-environments.

Mixing and displacement ventilation are total room volume ventilation methods. The ventilation airflow rate should be designed and controlled based on the level of room occupancy to enable energy-efficient operation. The ventilation airflow rates in E3 research study were designed based on European standard EN 16798 for ventilation where typical indoor climate category 2 and more demanding category 1 were followed.

Personalized ventilation air distribution methods target to provide fresh ventilation air directly to the micro-environment of a person and also with higher ventilation efficiency aim to lower cross-infection risk. Different types of personalized ventilation setups have been extensively studied with promising results. Still, these air distribution methods have rarely been utilized in real

buildings. Different personalized ventilation methods in previous studies (Melikov, 2004 and Melikov, 2016) are shown in Figure 1 and 2.

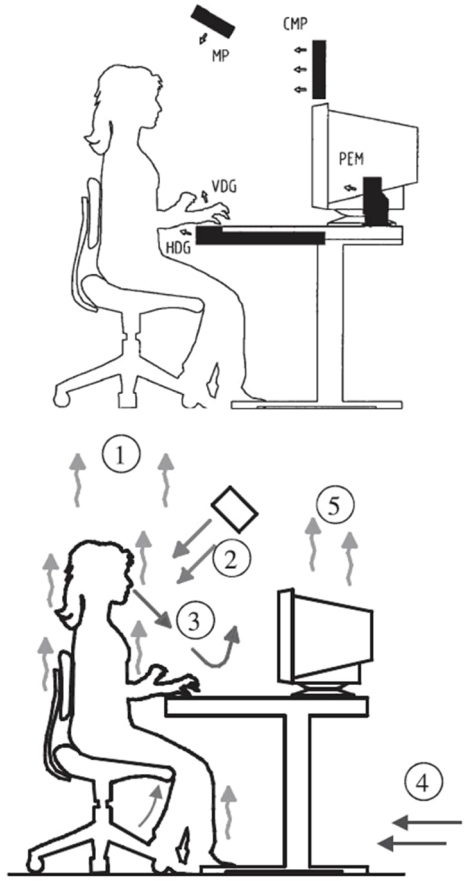

Figure 1: Examples of personalized ventilation air supply terminal devices (top) and airflow interactions around human body (below)

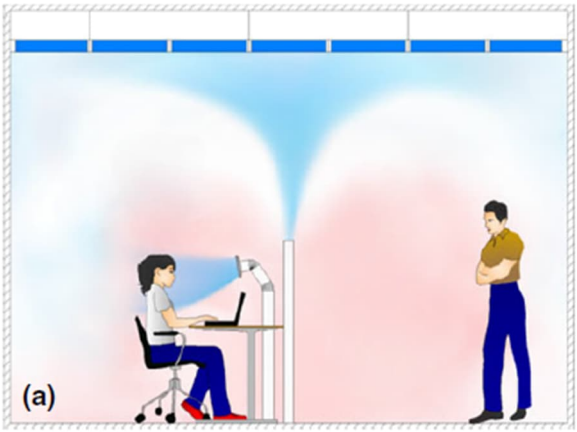

Figure 2: Personal ventilation combined with chilled ceiling (supply air distributed towards occupant at the workstation and from top of partition wall for providing air curtain between occupants

Covid19 pandemic and awareness of the importance of reducing the risk of all kinds of airborne infections, both ventilation methods and room air purification are important technologies for providing healthy indoor environments. Both were selected for the E3 research study. The room air purifiers can be used to enhance locally controlled micro-environments in multiple ways. Different kinds of setups were extensively studied in E3 research to provide a holistic view of reducing airborne infection risk in indoor environments.

7.1.3 Impact of E3 findings on controlled micro-environment

Experimental findings of E3 controlled micro-environment studies (see the following papers in the chapter) clearly show that special techniques for the creation of controlled micro-environment reduce aerosol exposures at the personal breathing zone more than at room breathing zone. Reductions up to 80% was recorded. However, it is important to mention that care should be taken when looking at the percentages given in this chapter. They are valid for the experimental arrangements used and, thus, may be different in other conditions.

There are several factors affecting the flow of aerosols in air, which all have an impact. Therefore, selection of air purification approach must be done in care. Recommended air purification approach depends largely on where the reduction of aerosol exposure is wanted – in a micro-environment at desks, or more broadly at the office room. Furthermore, when making the final choice of air purification approaches, one should consider also other parameters than not only the decrease of exposure, such as energy consumption, usability, thermal comfort, noise, price, etc.

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7.2 Experimental arrangements of E3 controlled micro-environment measurements

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Abstract: Here we present the experimental arrangements and different ventilation and air purification cases used in the E3 controlled micro-environment studies. The results of the measurements and simulations will be presented in the following chapters.

7.2.1 Introduction

Here we present an overview of the experimental arrangements used in the controlled micro-environment studies of E3 project. The studies cover both experimental studies at VTT's laboratories and CFD simulations. The main results of the experiments and the CFD simulations are reported in the following chapters 7.3 and 7.4.

The main research question of E3 controlled micro-environment studies was **How much the air quality could be improved with controlled micro-environment solutions?** The air quality improvement was considered as the decrease of exposure in respect to the basic mixing-type ventilation strategy.

We constructed a small office room mock-up inside VTT's test chamber in Rusko, Tampere. The office room was occupied with two persons sitting at their office desks and one person standing by the desk. One of them was a source of particle emission and the other two being affected by the emission. Different ventilation and air purification strategies and solutions were tested and compared. Additionally, the experimental arrangements aimed to provide comparable measurements in a controlled environment for CFD-model development and validation.

7.2.2 Test office room

Overview of the test office room is given in Figure 1, and the layout of the room in Figure 2. Persons in the room were modelled by heated cylindrical dummies: two sitting dummies (1 and 2) and a standing dummy 3. One of the dummies was source of controlled particle emission produced by a constant output aerosol generator. Particle exposure in the room was measured by 28 small and lightweight sensors: 9 Sensirion SPS30, 9 Alphasense R2, and 10 Alphasense N3 optical particle counters (OPCs). The OPCs were positioned to measure the

breathing zone of the dummies, as well as the spatial distribution of the particle emission throughout the room. A reference measurement was taken from exhaust of the room with a high-end Palas Fidas Frog OPC. The temperature of the room was measured at 15 points with PT100 temperature sensors to determine the possible spatial temperature gradients.

Floor area of the room was 16 m^2 and volume 40 m^3. Heath load in the room consisted of lights, dummies, computers, and a window, totalling a heat load of roughly 400W. Cooling panels in the ceiling with cooling power of 300 - 400 W and cool supply air were used to reach the room design temperature of 19°C, which was selected to minimize the heat loss to the external space. The air flow rate 36 l/s unless otherwise stated.

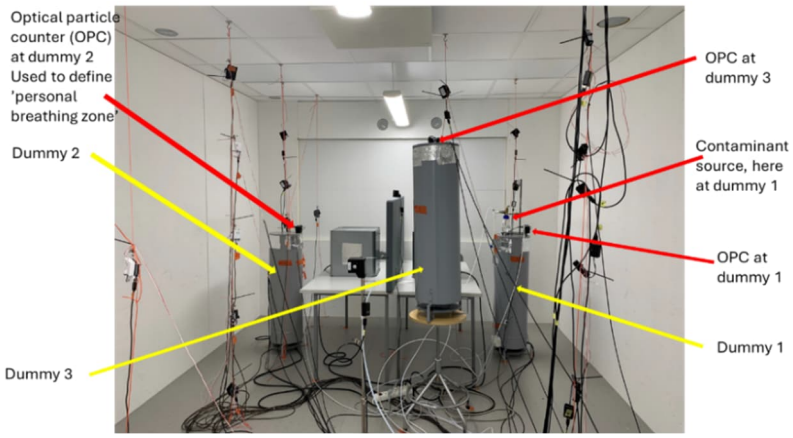

Figure 1. Overview of the office room mock-up.

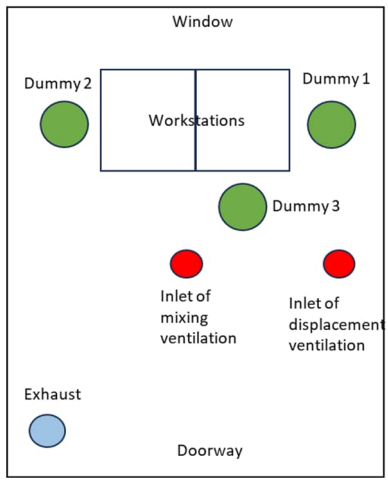

Figure 2. Layout of the office room mock-up.

7.2.3 Studied cases

Studied cases include different ventilation strategies, and cases of special techniques. The base cases were for mixing type of ventilation, with two air flow rates of 21 l/s and 36 l/s, and displacement type of ventilation, with an air flow rate of 36 l/s (Figure 3). Special technique cases include using different types of air purifiers in different locations, and additional air inlets or exhausts positioned above the workstations (Figure 4).

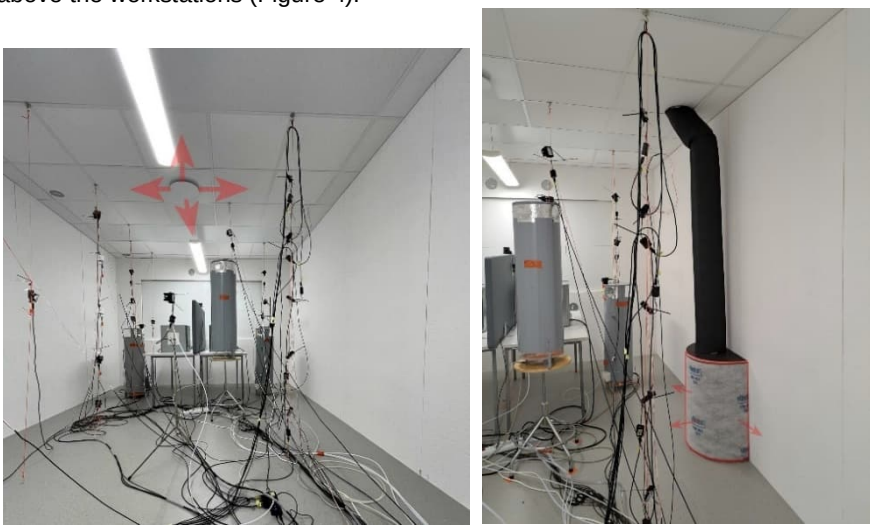

Figure 3. Basic ventilation cases: mixing ventilation (left) and displacement ventilation (right). Red arrows indicate the direction of air inlet.

Figure 4. Special ventilation approaches: additional inlets above the workstations (left), and additional exhausts above the workstations combined with displacement ventilation (right).

Air purifiers were used to affect the whole room (Figure 5) or provide local zones of clean air (Figure 6). The floor-standing air purifier was designed to

efficiently mix the airspace, whereas the ceiling mounted air purifier prototype was designed not to disturb the stratification caused by the displacement ventilation.

The desktop air purifiers directed a stream of clean air towards the breathing zone of the person occupying the desk. The ceiling mounted air purifier generated a laminar downward flow of clean air serving both desks. The air extraction for the laminar air purifier was either from the top or bottom corners of the room. It is worth noting, that the laminar air purifier was not installed according to the manufacturer's instructions due to the space limitations. The manufacturer instructed to mount the air purifier on the wall facing the occupant. When mounted on the ceiling, the upward draft from the heat sources works against the downward laminar flow creating less than ideal purifying effect.

More details of the approaches are given in Table 1.

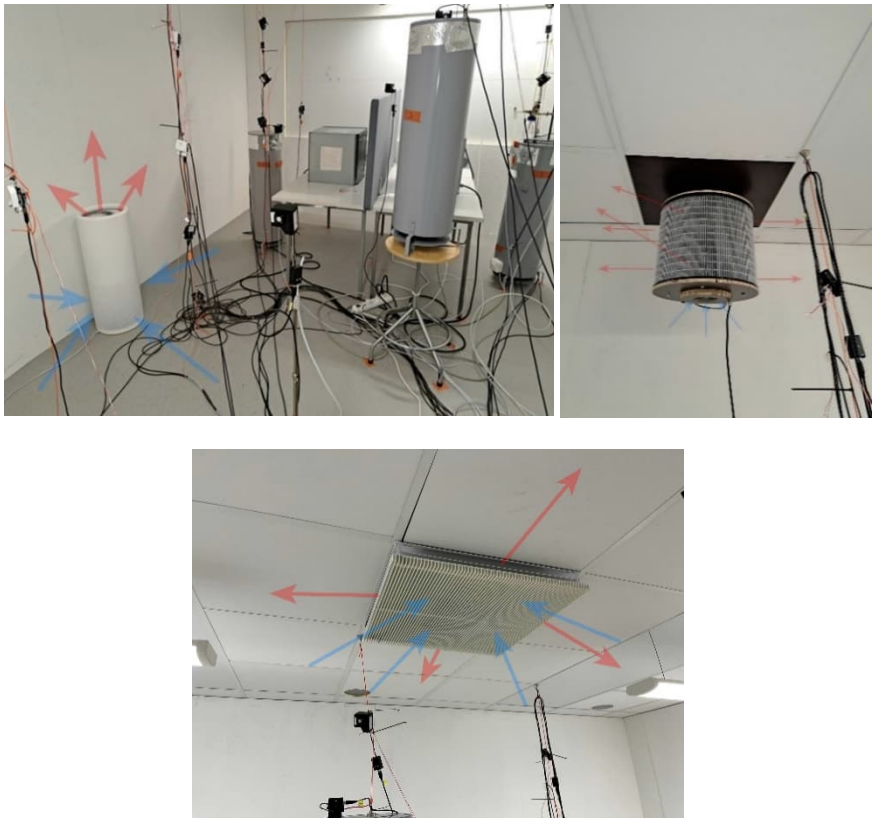

Figure 5. Special room level air purification approaches used in the experiments: Lifa LA 500 floor standing air purifier (top left), ceiling mounted air purifier prototype (top right), and Alme air purifying mixing inlet terminal (bottom). Red arrows indicate the direction of air inlet and blue arrows exhaust.

Figure 6. Approaches for local zones of clean air: Atem personal purifier on a desk (top left), Lifa LAX200 personal air purifier on a desk, ceiling mounted laminar air purifier with extraction from ceiling height (bottom). Red arrows indicate the direction of air inlet and blue arrows exhaust.

Table 1. Specifications related to the studied cases.

Case description	Code	Purifier CADR	Combined with mixing (M) or displacement (D ventilation (& rate)
Base case mixing ventilation	MC		21 or 36 l/s
Base case displacement ventilation	D		36 l/s
Air inlets above workstations. Exhaust as in the base case.	DAW		M 36 l/s
Extract air above workstations, displacing ventilation	EAW		D 36 l/s
Floor standing air purifier, type LIFA LA 500	PF	62 l/s	M 36 l/s or D 36 l/s
Ceiling type test purifier, type VTT proto	PC	62 l/s	D 36 l/s
Purifier as mixing inlet terminal, type Alme	PI	55 l/s	M 21 l/s
Atem personal air purifier on desk no. 2	PD2 or PD4	2 or 4 l/s	M 36 l/s
LIFA LAX200 personal air purifiers on one or two desks	2PD56,2PD44, PD28, PD22	22 or 28 l/s per device	M 36 l/s
ISEC air purifier on top of the workstations. Air circulation extraction from either “from ceiling” or from ”floor position”	PCWH (ceiling), PCWL (floor)	160 l/s	M 36 l/s

7.2.4 Concluding remarks

An overview on the experimental arrangements used in the controlled micro-environment studies of E3 project was given and a total of 10 different cases were described, some of them with different variations. The cases include base cases without air purifiers to demonstrate basic ventilation strategies, which are also used for reference purposes, and cases with special air purification techniques.

It is important to underscore that the purpose of this study was not to rank the air purification strategies nor the purifiers, but to gain an overall idea on how much the air quality could be improved with controlled micro-environment solutions.

Furthermore, positioning of the devices may not have been optimal for all the devices, nor the running parameters (air flow rates etc.). Considering the research question, the experimental arrangements provide sufficient case description for the studies reported in the following chapters 7.3 and 7.4.

7.2.5 Acknowledgements

We thank Jani Moberg from Alme Solutions, Janette Mäkipää from Lifa-Air, and Risto Salin from ISEC for providing air purification devices for the study.

7.3 Experimental findings of E3 controlled micro-environment studies

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Abstract: In this paper main findings of E3 controlled micro-environment experiments are reported. Air purification clearly reduces the exposure of persons, if compared to cases with basic ventilation only. Furthermore, controlled micro-environment with increased air quality could be created on workstations with special techniques.

7.3.1 Introduction

Controlled micro-environment studies in the E3 project were focused on finding answers to the research question **'How much the air quality could be improved with controlled micro-environment solutions?'** The air quality improvement was here considered as the decrease of exposure in respect to cases with basic ventilation only. This paper presents key experimental findings of the controlled micro-environment studies. The paper is closely related to other two papers in this E3 Final Report: Paper 7.1 by Paasi & Mustakallio, where the motivation and conclusions of the study are given, and paper 7.2 by Hakala et al., where experimental arrangements and studied cases are presented. When reading the findings of this paper, it may be good at the same time to look paper 7.2 for more details on the studied cases.

This paper is arranged as follows: At first, key findings from base cases will be presented to understand the flow of exposures in the room. After that, key findings from cases of special techniques with air purification are presented.

7.3.2 Findings of base cases

The experiments began by studying base cases without air purification. In Figure 1 the impact of mixing and displacement ventilation on exposure at room level was compared in the case when the source of particles was dummy 2. Air flow rate was 36 l/s in both approaches. The x-axis in the figure is normalised concentration of PM2.5 particles, normalization done against the concentration of exposure. The y-axis is the height of optical particle counters (OPC) in the room. Black dots (with error bars) are room averages of exposure at the given height in the case of mixing ventilation, and red squares (with error bars) corresponding values for the case of displacement ventilation. The key finding in Figure 1 is that displacement

ventilation leads to clear vertical stratification of aerosol exposure within room, clean air being at the bottom of room. Mixing ventilation effectively mixes the aerosol exposure around the room.

From the viewpoint of controlled micro-environment, the most interesting values of exposure are those at heights corresponding the zone where the heads of persons in the room are. Taking into account that some persons may sit by their desk and other may stand, we define breathing zone between heights 120-180 cm. Average over the breathing zone will play an important role in the study of controlled micro-environment. In Figure 1, the breathing zone averages are indicated by dashed vertical lines. We can see that breathing zone exposure with displacement ventilation is 29% lower than with mixing ventilation.

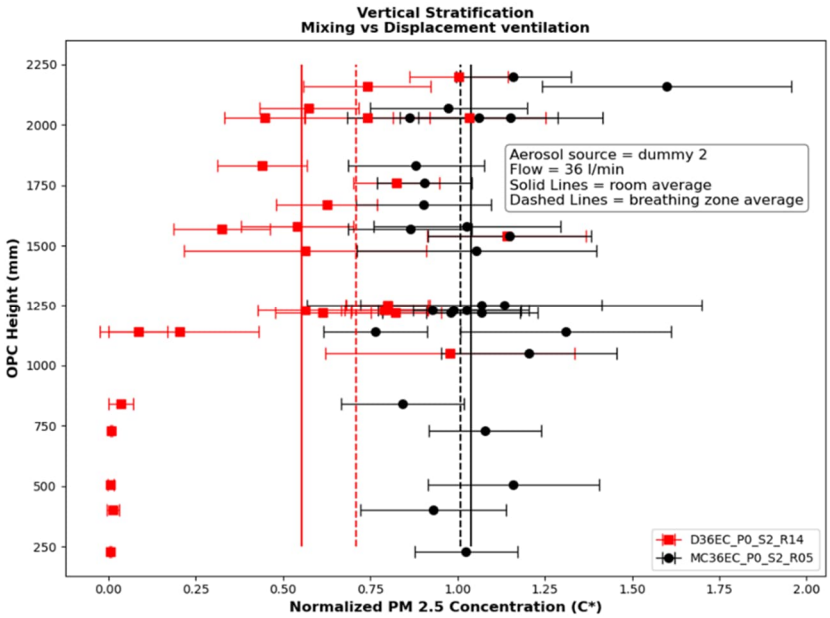

Figure 1. Aerosol exposure at different heights in the cases of mixing and displacement ventilation without air purification

The second base case was to gain an overall understanding on the impact of air purification in the case of displacement ventilation at different heights of room. Two different techniques were selected for this study: a floor standing air purifier code PF, and ceiling type test purifier code PC, see paper 8.2 for more details. Clean air delivery rate (CADR) was 62 l/s for both devices. The results are shown in Figure 2, where the reference was displacement ventilation at 36 l/s without air purifiers. The x-axis in this figure is the absolute concentration of PM 2.5 particles, and the y-axis height of OPCs. From the figure we can see that air purification reduces aerosol exposure. In the breathing zone the reduction using the floor purifier is 26% and using the ceiling purifier 57%. The floor standing air purifier

essentially acts as a mixing fan, breaking down vertical stratification from displacement ventilation. The ceiling mounted air purifier maintains vertical stratification but lowers overall aerosol exposure.

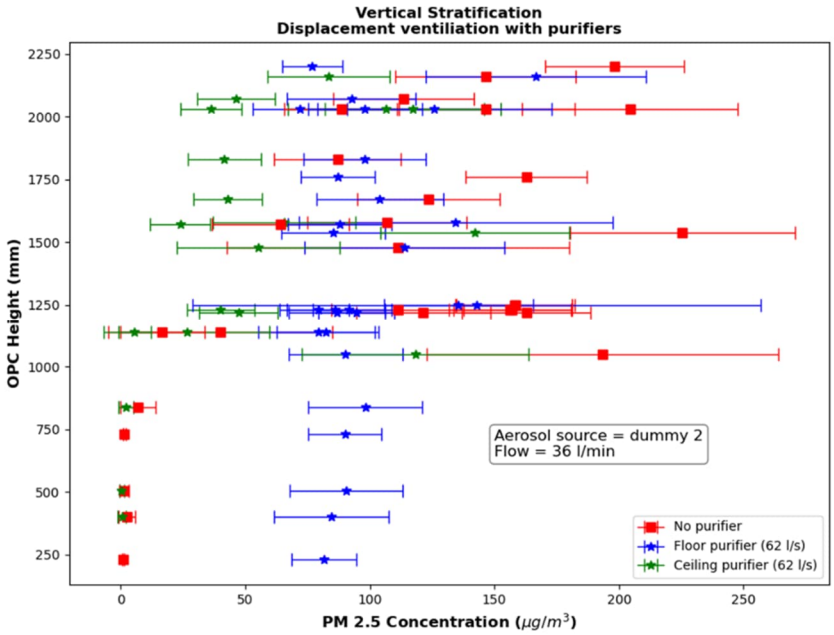

Figure 2. Aerosol exposure at different heights in the cases of displacement ventilation with air purifiers

7.3.3 Findings of special technique cases

Impact of air purifiers to aerosol exposure can clearly be seen in Figure 3 where different air purification techniques were used. PM 2.5 concentrations are given for each as a room average and a breathing zone average. On top of bars is the percentage of aerosol exposure reduction when compared to relevant base case without air purifiers (mixing ventilation with 21 l/s or 36 l/s or displacement ventilation with 36 l/s). The cases in the figure are (from left to right): base displacement ventilation case, LIFA LA500 floor standing purifier ‘PF’ (CADR 62 l/s) combined with displacement ventilation, VTT proto ceiling purifier ‘PC’ (CADR 62 l/s) combined with displacement ventilation, ALME mixing inlet terminal purifier ‘PI’ (CADR 55 l/s), ATEM personal desk purifier ‘PC’ with CADR 4 l/s and 2 l/s, LIFA LA500 floor standing purifier ‘PF’ (CADR 62 l/s) combined with mixing ventilation, ISEC ducted overhead purifier ‘PCW’ (CADR 160 l/s) with air circulation extraction from ceiling ‘PCWH’ and floor ‘PCWL’, LIFA LAX200 personal desk purifier on one desk with two CADRs of 28 l/s and 22 l/s and on two

desks with summed CADRs of 56 l/s and 44 l/s, and base mixing ventilation cases with 21 l/s and 36 l/s. Source of aerosol was dummy 1. From the figure we can see that purification is effective for entire room. If compared to relevant reference case without air purification, LIFA LA500 resulted in 53-55% lower aerosol exposure in the breathing zone, VTT proto 63% lower exposure, Alme 73% lower exposure, Atem 23% lower exposure, LIFA LAX200 on desk 2 38-50% lower exposure and on both desk 59-66% lower exposure, and ISEC 78-81 lower exposure. However, one should not rank the techniques based on just these measurements, because not all devices were positioned and used optimally. Furthermore, the position of exhaust does have an impact to the results and will favour some techniques more than others.

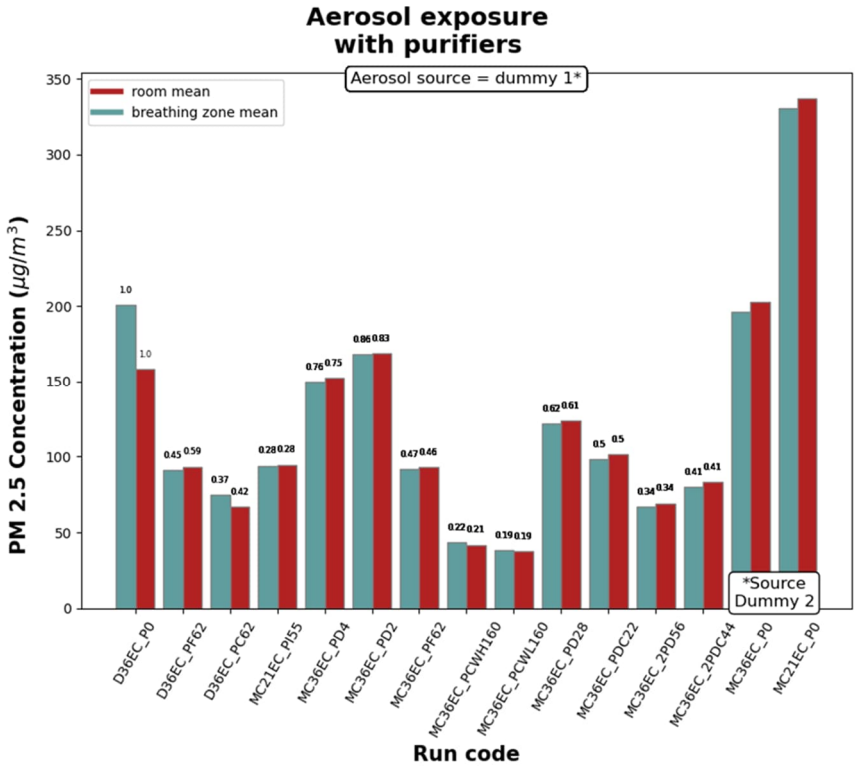

Figure 3. Aerosol exposure with the studied air purifiers. PM 2.5 concentrations normalized against relevant reference case are given above the bars.

From the viewpoint of controlled micro-environment, the most important situation is the exposure in personal breathing zones that corresponds to area around the nose of person. In the experimental arrangement the personal

breathing zone was measured by the OPC on the top of dummy. When a dummy was the source of aerosols, the OPC was moved few centimetres backwards. Figure 4 is a summary of measurements done for cases presented in paper 8.2. Each dummy was in turn the source of aerosols. The figure includes bars for the PM2.5 concentration corresponding to room average, breathing zone average, and personal breathing zones of each dummy (although the breathing zone of the dummy being the aerosol source do not have a practical sense). There are some empty cases in the figure due to missing data, but still sufficient data to make key findings. We do not go here into the details of data in Figure 4, but mention as the key finding that personal breathing zone at dummy location typically faces lower aerosol exposure than room breathing zone. This indicates that the personal air purification strategies work, in general, in the creation of micro-environment with improved air quality if compared to surroundings. Furthermore, one could say that the standing dummy (3) typically faces slightly higher exposure than the sitting dummies (2) when air purification is used. Also, there are slightly lower concentrations when source is dummy 3.

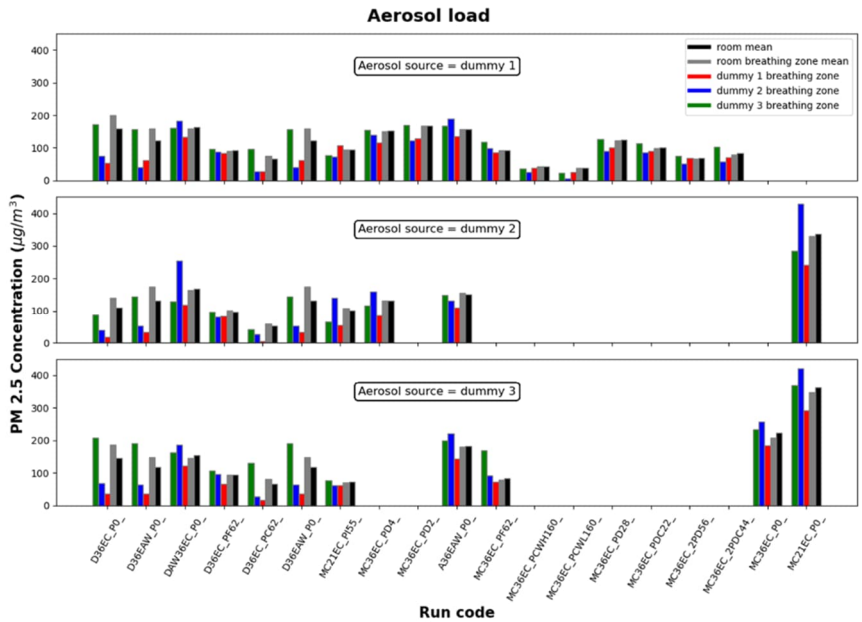

Figure 4. Aerosol exposures ‘room mean’, ‘breathing zone mean’, ‘personal breathing of dummy 1’, ‘personal breathing zone of dummy 2’, and ‘personal breathing zone of dummy 3’ for the studied cases.

Air purification devices used in the study have different CADRs. To see the effect of CADR to aerosol exposure, the measurement data was presented as a

function CADR in the studied cases. In Figure 5 the aerosol exposure in room breathing zone as a function of inverse CADR is presented, and in Figure 6 personal breathing zones of sitting dummy 2 and standing dummy 3 as a function inverse CADR. An additional x-axis is set below both figures to help readers to identify real CADRs of cases in the figures. From Figure 5 we can see that the reduction of exposure at room breathing zone is roughly linear (within the limits of measurement accuracy) with inverse of CADR, which is in line with theoretical expectation. The higher the CADR, the higher the reduction.

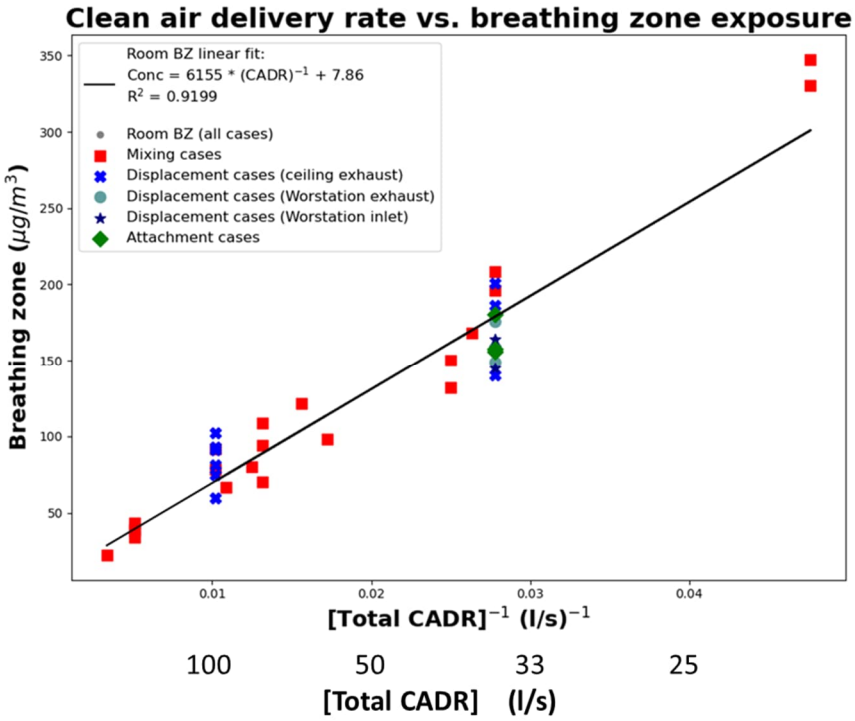

Figure 5. Clean air delivery vs. room breathing zone exposure for all the studied cases

Figure 6 shows that the reduction of exposure at personal breathing zone of standing dummy 3 is in line with the theoretical 'CADR expectation' for room breathing zone, but the reduction of exposure at the sitting dummy 2 exceeds the theoretical room breathing zone expectation. This clearly demonstrates the presence of micro-environment at the sitting dummies with improved air quality in comparison to surroundings. The circled two red squares with low exposure are due to stratification in the case of displacement ventilation without purifiers. A good local micro-environment was created, but the height of stratification layer

may not be well controlled in practice where there may be more elements disturbing the designed flow of air than in the studied laboratory room.

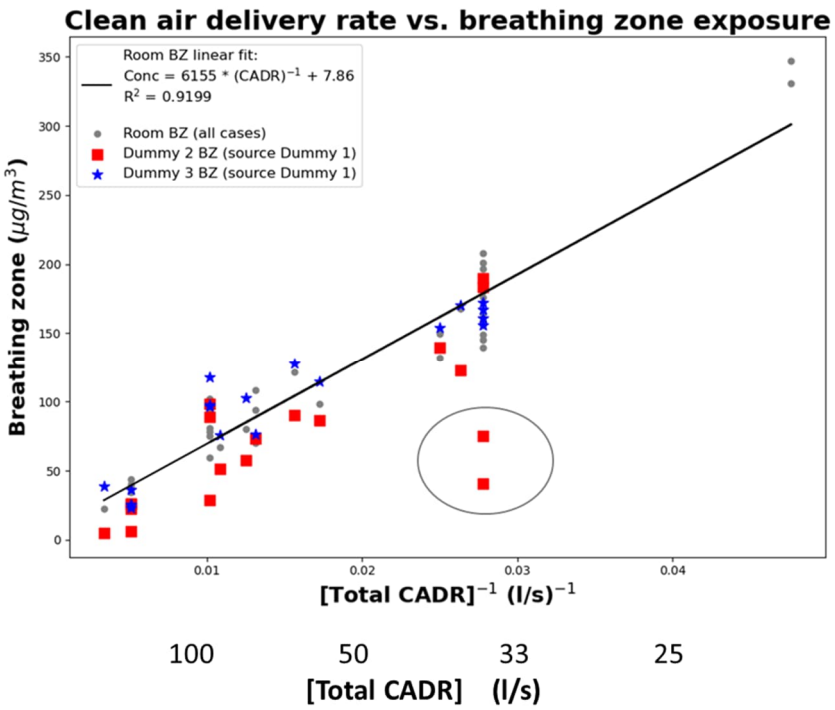

Figure 6. Clean air delivery rate vs. personal breathing zone exposure for the studied cases.

7.3.4 Conclusions

Ventilation and every room air purifier type essentially reduce aerosol exposure at the breathing zone. Displacement ventilation lowered exposure compared to mixing ventilation cases also without an additional air purifier. Reduction of exposure is roughly linear with inverse of clean air delivery rate, in line with theoretical expectation. The higher the clean air delivery rate, the higher the reduction. Special techniques focusing to personal breathing reduces aerosol exposures at the personal breathing zone more than at room breathing zone, thus creating controlled micro-environment.

7.3.5 Acknowledgements

We thank Jani Moberg at Alme Solutions, Janette Mäkipää at Lifa-Air, and Risto Salin at ISEC for providing air purification devices for the study.

7.3.6 References

Paasi, J. & Mustakallion, P. (2024). Controlled micro-environments for locally improving indoor air quality*, in E3 Final report*

Hakala, J., Kultanen, M., Säämänen, A., Karvinen, A., Paasi, J., Asmi, E., Mustakallio, P. (2024). Experimental arrangements of E3 controlled micro-environment measurements, *in E3 Final report*

7.4 CFD findings from the office analysis

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Abstract: This research investigated the office environment through simulation, running multiple simulations across a variety of cases. The simulation results show well the pros and cons of different ventilation or purifying strategies. Since there were dozens of cases, the Reynolds-Averaged Navier-Stokes (RANS) method, which is easier in terms of computing capacity requirements, has been used in this study. The results are evaluated against the empirical data. Additionally, some of the cases are simulated using the detached eddy simulation (DES) method for validation purposes.

7.4.1 Introduction

According to some studies people spend over 90 % of time indoor. In certain professions, most work hours are spent in office environments. Ensuring a safe workplace, particularly during a pandemic, is crucial. Consequently, an office space has been selected as the focus of this research. The study examines its pandemic safety using computational fluid dynamics (CFD).

7.4.2 Cases studied

A mock-up office (Figure 1) mimics an office setting, featuring two workstations. In addition to the humans sitting next to the tables (dummy1 and dummy2), there is individual who is standing (dummy3).

To minimise heat loss in our experimental chamber, the design temperature is set to 19°C rather than the standard 20...23°C. This change is valid as the temperature itself has only little effect on air flows; what truly influences them is the temperature difference. Other temperatures and heat loads were:

- Inlet air temperature: 12°C (this is also below the usual range due to the lower design temperature)
- All dummies: 75 W each
- Computers: 80 W each
- Lights: 60 W each
- Window: 100 W (the 0 W case was also examined, but not reported here)
- Radiators: -150, or -200 W depending on the case

It was assumed that all other surfaces—floor, walls, ceiling, and furniture—were fully insulated (adiabatic). Given the nearly identical design temperature to the larger hall where the mock-up office was constructed, this assumption is justifiable. This was confirmed by heat balance calculations.

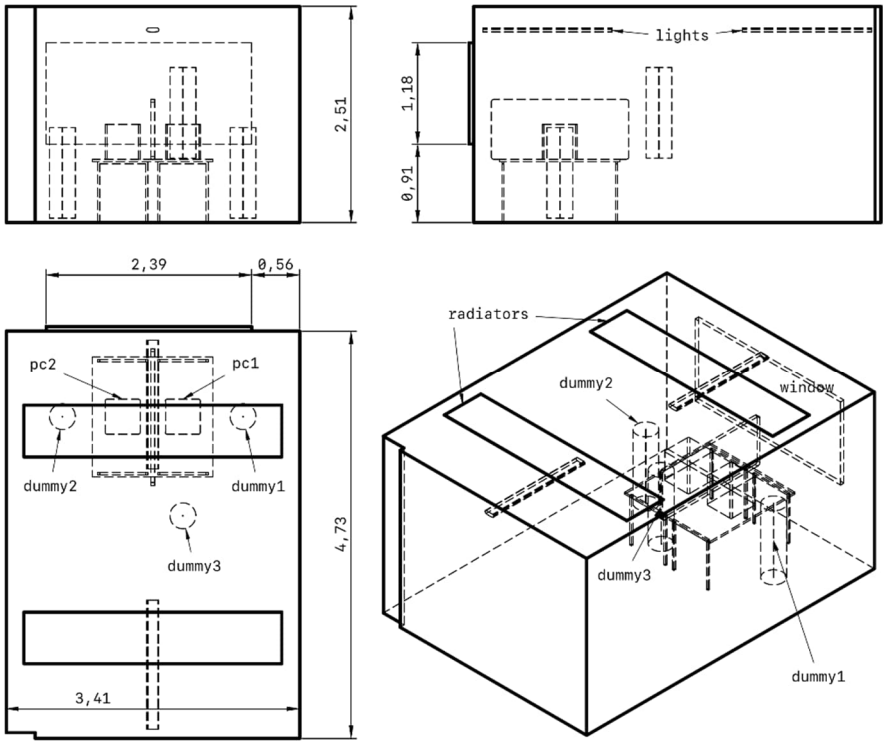

Figure 1. A simulated office space and its main dimensions. All lengths are given in meters.

Figures 2 and 3 illustrate the various ventilation and air purifying strategies investigated. Figure 2 depicts a standard mixing supply air device positioned centrally on the roof and a standard displacement ventilation unit located near the wall. Additionally, it indicates the placement of the exhaust ventilation device used in majority of the studies. The figure also indicates the position of the floor-type air purifier. It's important to note that these devices were not used at the same time, even though they are shown together in the figure.

Figure 3 illustrates the laminar-type flow air distribution units positioned above the workstations. The flow from these devices is not completely laminar, although the devices are called laminar-type. These devices are designed to create a safe workspace for seated individuals.

The second approach shown in Figure 3 involves placing the outlets proximate to the source, specifically positioning one outlet above both workstations. This strategy aims to eliminate pollutants from the area of occupants as soon as possible. The second device featured in the top right figure is a ceiling-mounted air purifier, used with displacement ventilation. Floor-based air purifiers are less effective with displacement ventilation as they reside in the cleaner zone already created by the ventilation system. Furthermore, deploying a floor-based air purifier

mixes the air, compromising the advantages of displacement ventilation. The ceiling-mounted air purifier is designed to produce an airflow that is intentionally slow and close to laminar as possible, minimizing mixing effect.

Figures on bottom row illustrate a laminar-type air purifier positioned atop workstations. The left image depicts the purifier drawing air from the ceiling level, while the right one shows it extracting air from the floor level.

In addition, a situation has been tested where the mixing supply air system has been replaced with a supply air system that purifies the room air. This circulates the room air so that, in addition to acting as a supply air device, it acts as an air purifier with a clean air delivery rate (CADR) of approximately 2.6 times the amount of clean supply air.

The final two scenarios involve the placement of personal air purifiers on one or both tables. When orientation is needed, the purifier is positioned to deliver clean air as precisely as possible towards the individual next to the table. The cases are summarised in the Table 1.

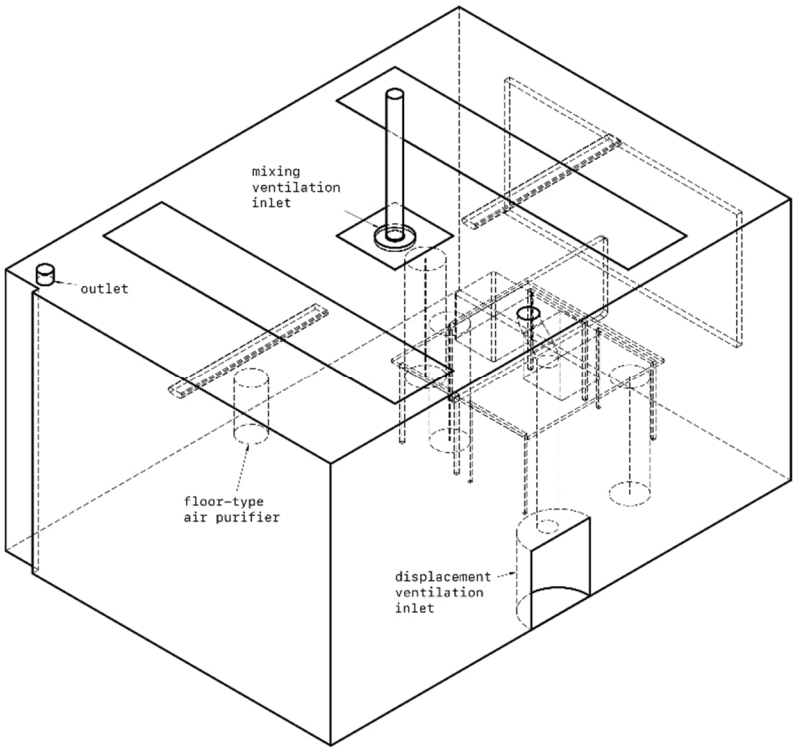

Figure 2. Basic ventilation strategies (mixing and displacement) and floor-type air purifier.

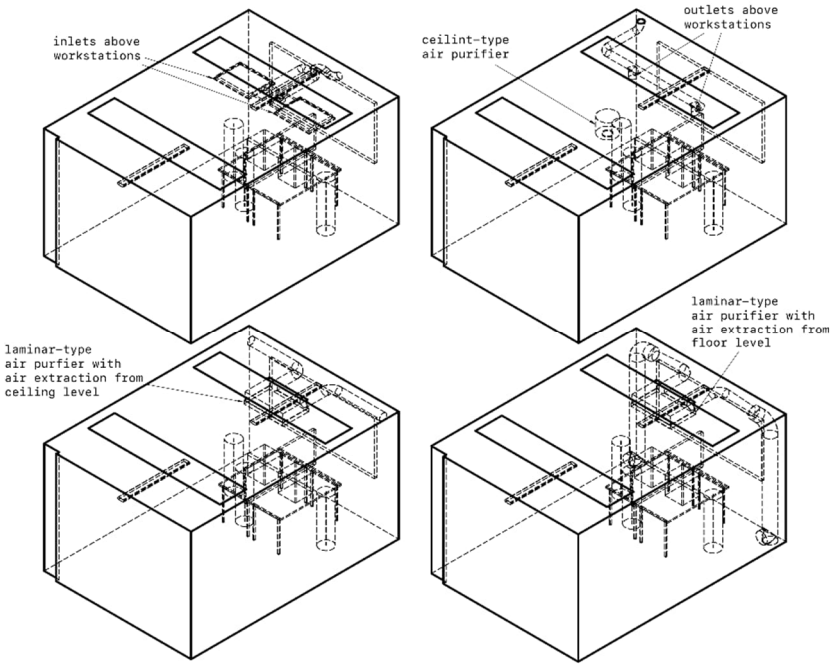

Figure 3. Various ventilation and air purification strategies used in the study.

Table 1. Cases studied.

Case description	**Code**	**Purifier CADR**	**Combined with mixing (M) or displacement (D ventilation (& rate)**
Base case mixing ventilation	MC21, MC36		21 or 36 l/s
Base case displacement ventilation	D		36 l/s
Air inlets above workstations. Exhaust as in the base case.	DAW		M 36 l/s
Extract air above workstations, displacement ventilation	EAW		D 36 l/s
Floor standing air purifier, LIFA 500	PFM36, PFD36	62 l/s	M 36 l/s or D 36 l/s
Ceiling type test purifier, VTT proto	PC	62 l/s	D 36 l/s
Purifier as mixing inlet terminal, Alme	PI	55 l/s	M 21 l/s
Atem personal air purifier on desk. 2	PD2 or PD4	2 or 4 l/s	M 36 l/s
LIFA LAX200 personal air purifiers on one or two desks	2PD56,2PD44, PD28, PD22	22 or 28 l/s per device	M 36 l/s
ISEC air purifier on top of the workstations. Air circulation extraction from either “from ceiling” or from ”floor position”	PCWH (ceiling), PCWL (floor)	160 l/s	M 36 l/s

7.4.3 Methods and models

The open-source software OpenFOAM (org version) is employed. Due to the characteristics of indoor airflow, obtaining fully convergent results with steady-state simulation is impossible. Thus, an iteration average is used. The total number of iterations is 1,000,000, with results averaged over the last 500,000 iterations. Turbulence is modelled using the SST k-ω model (Menter, 1994).

In addition to the RANS method, one case has also been simulated using the DES method, i.e. SST k-ω DES (Menter et al., 2003) for validation purposes.

Three scenarios are considered where dummy1, dummy2, or dummy3 is sick (index person) while the other two are healthy. The sick individual emits particles (modelled as a passive scalar), and the concentration in a steady-state situation is analysed at several locations, which include:

- entire room (volume average)
- breathing zone (height = 1.2 to 1.8 m)
- breathing zones of healthy individuals
- positions of 15 T sensors
- positions of ten N sensors
- positions of nine R sensors
- positions of nine S sensors (presented in Figure 4)
- Because of space constraints, only a portion of the results is presented here.

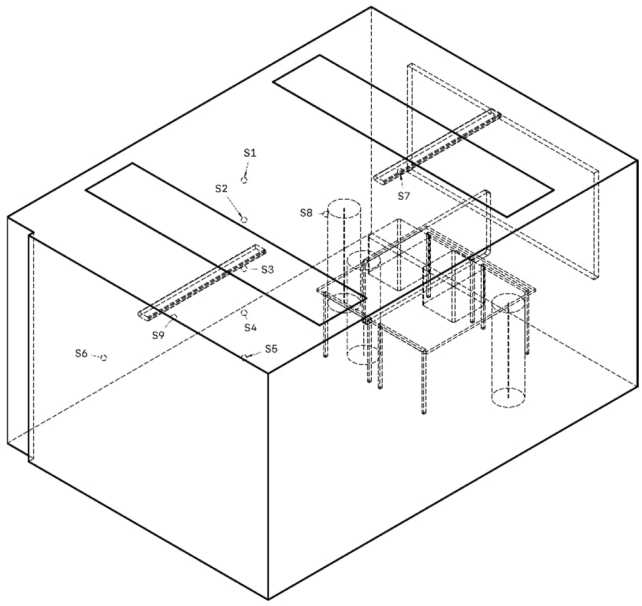

Figure 4. Sensor S locations: S1 through S5 are positioned in a vertical line, while S6 through S9 are arranged horizontally. These lines intersect at one point.

7.4.4 Results – Validation

Table 2 presents the ventilation efficiency for both mixing and displacement ventilation scenarios at the sensors illustrated in Figure 4. The correlation between the measured data and simulations is generally positive, although there are significant discrepancies in the displacement ventilation case in the S4 and S5 locations. Despite these differences, the overall trend remains acceptable.

Ventilation efficiency is used as a measure here because concentration is not a usable metric due to different (unknown) emission rates.

Table 2. Ventilation efficiency at sensor locations. It is important to highlight that, unlike other instances in this research, the MC case here uses dummy3 as the index person (all other cases use dummy1).

	MC		D		
Sensor	**exp.**	**RANS**	**exp**	**RANS**	**DES**
S1	0.95	0.97	0.95	0.98	0.99
S2	1.11	0.96	1.13	1.10	1.06
S3	0.93	0.97	0.90	1.11	1.07
S4	0.93	0.99	75.01	1.47	2.00
S5	0.96	0.99	97.90	3.01	2.62
S6	1.04	0.97	1.07	0.97	1.02
S7	0.96	0.95	1.08	1.30	1.37
S8	0.98	0.97	0.95	1.09	1.07
S9	1.00	0.98	0.90	1.06	1.05

7.4.5 Results – Findings

Table 3 provides a summary of the results across various cases. The base case, which is the mixing ventilation case with a ventilation rate of 36 l/s, is used as the reference for comparison against other cases. When rating the different scenarios, it is important to consider the significant variation in the total ventilation.

Some findings vary from the measured data (detailed in another section of this report), necessitating additional investigation to determine the reasons. One plausible reason is the insufficient accuracy of heat load estimations in simulations. It is difficult to determine the exact heat loads in experiments. Moreover, accurately accounting for heat loads in simulations is challenging.

Figure 5 illustrates the distinction between mixing and displacement ventilation at the symmetry plane of the room. The figure indicates that increasing the room's height does not resolve the issue of the stratification layer in displacement ventilation being too low. Conversely, a ceiling-mounted air purifier enhances the pandemic safety of a displacement ventilation scenario, provided it does not inadvertently create a mixing ventilation situation.

This article presents only a very limited selection of the findings and does not delve into why certain ventilation or air purification methods outperform others. Additional results and discussion will be included in forthcoming articles and reports.

Table 3. Particle concentration compared with Base case mixing ventilation with 36 l/s (Code MC36) across various regions. Index person (source) is dummy1. When rating the different scenarios, it is important to consider the significant variation in the total ventilation.

Case description	**Code**	Entire room	Breathing zone (1.2...1.8m)	Dummy2 breathing zone	Dummy3 breathing zone
Base case mixing ventilation	MC21	1.57	1.53	1.55	1.54
Base case mixing ventilation	MC36	1.00	1.00	1.00	1.00
Base case displacement ventilation	D	0.88	0.91	0.66	0.90
Air inlets above workstations. Exhaust as in the base case.	DAW	0.64	0.63	0.50	0.65
Extract air above workstations. displacement ventilation	EAW	0.90	0.76	0.53	0.75
Floor standing air purifier. type LIFA LA 500	PFM36	0.34	0.43	0.33	0.46
Floor standing air purifier. type LIFA LA 500	PFD36	0.35	0.51	0.36	0.43
Ceiling type test purifier. type VTT proto	PC	0.33	0.46	0.24	0.50
Purifier as mixing inlet terminal. type Alme	PI	0.70	0.72	0.71	0.73
Atem personal air purifier on one desk (close to dummy2)	PD2	0.96	0.97	0.97	0.97
Atem personal air purifier on one desk (close to dummy2)	PD4	0.92	0.92	0.89	0.93
LIFA LAX200 personal air purifiers on two desks	2PD56	0.37	0.39	0.34	0.40
LIFA LAX200 personal air purifiers on two desks	2PD44	0.47	0.51	0.47	0.57
LIFA LAX200 personal air purifiers on one desk (close to dummy2)	PD28	0.51	0.54	0.49	0.56
LIFA LAX200 personal air purifiers on one desk	PD22	0.66	0.74	0.70	0.75
ISEC air purifier on top of the workstations. Air circulation extraction from ceiling level	PCWH (ceiling)	0.20	0.09	0.06	0.12
ISEC air purifier on top of the workstations. Air circulation extraction from floor level	PCWL (floor)	0.17	0.16	0.05	0.12

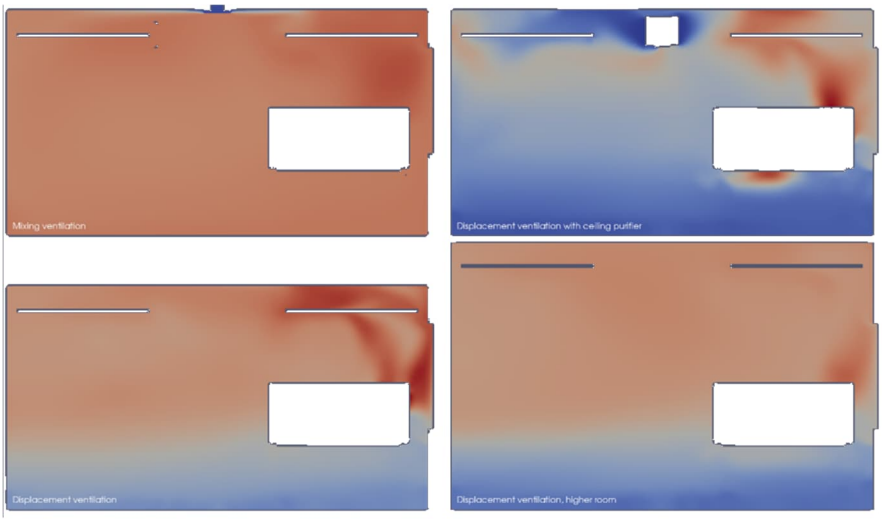

Figure 5. Concentration of the dummy1 emitted impurity in the symmetry plane using mixing ventilation (top left), displacement ventilation (bottom left), displacement ventilation in a higher room (bottom right), and displacement ventilation in the original height room with a ceiling-mounted air purifier. Blue indicates a low concentration, while red means a high concentration.

7.4.6 Conclusions

The mixing situation within the room is very well achieved, ensuring a constant distribution of particles. However, while displacement ventilation effectively creates visible stratification, this stratification layer is positioned too low to guarantee a clean breathing zone for the occupants. Elevating the room height does not assist in raising the stratification layer. Nevertheless, the ceiling-mounted air purifier introduced into the upper section of the polluted air proves highly effective, making the displacement ventilation scenario commendable.

The results also show that by designing and implementing personal ventilation correctly, a pandemic-safe space can be produced, especially for sitting people, without increasing the overall clean air delivery rate. Additional results and discussion will be included in forthcoming articles and reports.

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7.5 Use of the Tracer Gas in Studying Airborne Respiratory Infection Transmission in a Full-Scale Test Room

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Abstract: Reducing infectious aerosols in office environments is vital for public health, particularly during pandemics. Effective ventilation can significantly lower airborne viral particle concentrations, reducing respiratory infection risks. This study used tracer gas techniques to evaluate ventilation performance in removing airborne contaminants. By measuring several performance parameters, the study aimed to identify the most effective ventilation strategies for minimizing airborne infection transmission in office settings. Results highlight the importance of optimized ventilation in enhancing indoor air quality and reducing infection risks.

7.5.1 Introduction

Reducing infectious aerosols in office environments is crucial for maintaining public health, especially during pandemics. Offices are high-density environments where people spend extended periods, increasing the risk of airborne disease transmission. Effective ventilation can significantly reduce the concentration of airborne viral particles, thereby lowering the risk of respiratory infections among occupants.

Tracer gas techniques are widely used to study the contaminant removal performance of ventilation. Tracer gas methods can provide detailed insights into air distribution patterns, ventilation rates, and the efficiency of contaminant removal (Brouns and Waters, 1991, Mundt et al., 2004).

The goal of the tracer measurement campaigns presented in this paper was to evaluate several performance parameters for each scenario, indicating the ventilation system's capability to remove airborne contaminants and prevent occupants from being exposed to infectious respiratory aerosols. By focusing on these parameters, the study aimed to identify the most effective ventilation strategies for reducing the risk of airborne infection transmission in office environments.

7.5.2 Materials and Methods

An overview of the experimental arrangements used in the controlled micro-environment studies of E3 project is given elsewhere (Hakala et al., 2024). In this study, SF_6 was used as the tracer gas. Tracer gas experiments were done only in the cases without the air purifiers. This was because air purifiers were not able to remove tracer gas used.

Tracer gas was released from the top of a dummy through the same tubing as the DESH aerosol release, controlled by a mass flow meter at a rate of 35 ml/min and diluted with 6 l/min of air. The release time was set to ten times the nominal time constant of the room ventilation system to reach steady-state concentrations.

Sampling was conducted using a multiplexing valve system with four sampling lines. One line at the time was connected to the IR analyser (BINOS), while the others were under flushing. The sampling frequency was one minute per sample line, resulting in a sample every four minutes from each line. Sampling was done at the breathing zone level, with three samples taken in each measurement. Two samples were from the breathing zone of the dummies, excluding the dummy used as the index person. One sampling point was in an area without dummies, called area sampling. Concentration in the extract air was measured in every experiment (Figure 1).

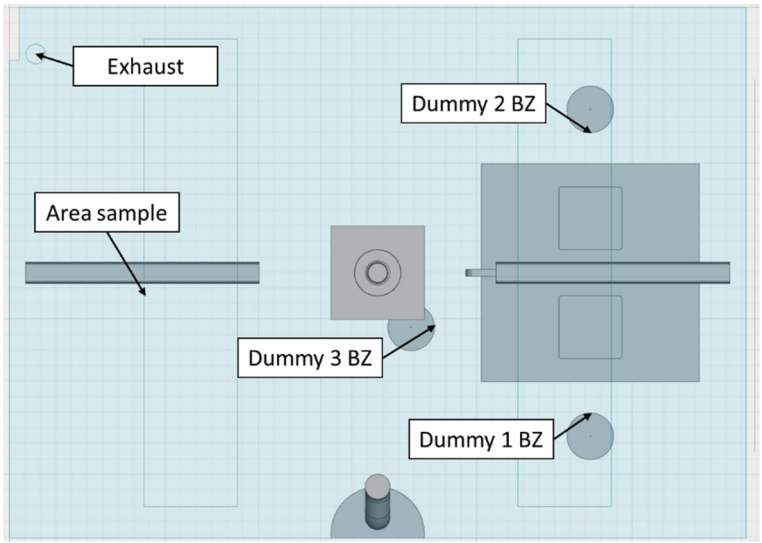

Figure 24. Locations of the tracer gas sampling points. Cool air supply was either from the ceiling diffuser (mixing ventilation) or from the low-velocity supply air diffuser at the floor level (displacement ventilation)

Several ventilation performance indicators were calculated. In this paper, we report steady-state concentrations and local air quality indexes. Firstly, the steady-state concentration of the tracer gas was calculated to simply visualise the ability of the ventilation to decrease contaminant concentrations in the room.

Tracer measurements were also used to calculate local air quality index, which characterizes the local efficiency of ventilation in a steady-state situation. Local air quality index at point p (ε_p^C) is defined with equilibrium concentrations in the extract air C_e and at point p C_p as follows:

$$\varepsilon_p^C = \frac{C_e(\infty)}{C_p(\infty)}$$

7.5.3 Results

As shown in Figure 2 the lowest concentrations were obtained with the displacement ventilation strategy ($p<0.05$). The highest concentrations were measured with mixing ventilation at 21 l/s, as expected. Attachment ventilation, local supply over dummies, and mixing ventilation at 36 l/s all resulted in similar average exposures.

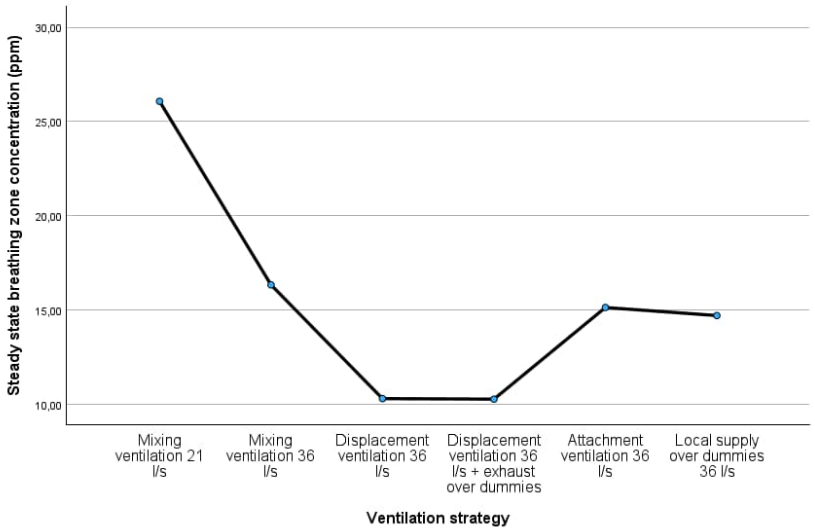

Figure 25. Average steady-state concentration in experiments using different ventilation strategies. The average of breathing zone concentration was calculated as a mean of all breathing zone concentrations in all experiments (different source dummies) using the same ventilation strategy.

The local air quality index serves as a multiplier for the effective air flow rate (Figure 3). According to REHVA, the local air quality index should be used to quantify health-based targeted ventilation rates. In mixing ventilation, local air quality index values were close to 1, while local supply over dummies and attachment ventilation also had values close to 1. In displacement ventilation cases, average breathing zone local air quality index values exceeded 2.

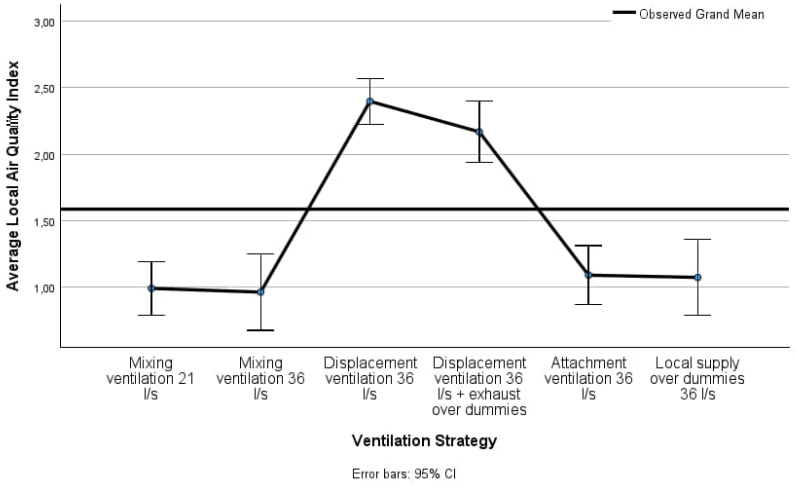

Figure 26. Average local air quality index in experiments using different ventilation strategies. The average local air quality index was calculated as a mean of all local air quality indexes in all experiments (different source dummies) using the same ventilation strategy.

7.5.4 Discussion and Conclusions

The tracer gas method proved to be an effective tool for studying airborne respiratory infection transmission in a full-scale test room. Kurnitski et al. 2023 applied the tracer gas method to measure airborne respiratory infection transmission in space mimicking the classroom (Kurnitski et al., 2023). They measured point source ventilation effectiveness, called the local air quality index, to study air distribution and breathing zone ventilation rate. It helps in calculating the design ventilation rate for actual air distribution systems.

This study highlighted the importance of ventilation strategies in controlling contaminant concentrations and reducing infection risks. In the studied case where the supply air was cooler than the room air and disturbances in the room were weak, displacement ventilation was the most effective strategy. The displacement ventilation strategy significantly lowered breathing zone concentrations and transfer indexes. Local air supply over the dummies was inefficient, likely because of the area covered by the supply was too small, and because the supply airflow rate was inadequate.

The study also emphasised the need for targeted ventilation rates based on health considerations, as recommended by REHVA. The local air quality index was a useful metric for evaluating ventilation effectiveness and guiding the design of ventilation systems.

Overall, the findings suggest that optimising ventilation strategies can significantly enhance indoor air quality and reduce the risk of airborne infection

transmission. Future research should continue to explore the application of tracer gas methods in various indoor environments to refine ventilation guidelines further and improve public health outcomes.

7.5.5 Acknowledgements

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7.6 Choosing, proper use and sizing of air purifiers

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Abstract: This article provides recommendations for the selection, proper use, and sizing of air purifiers to improve health and air quality. Choosing between laminar and mixing techniques depends on the needs. The placement of the air purifier is critical and needs great expertise. Careful planning may cut environmental exposure 20-fold and reduce illnesses and sick leaves significantly.

7.6.1 Introduction

The objective of this article is to provide recommendations for the selection, sizing, and proper use of air purifiers. The operation of ventilation affects purifier recommendations, and therefore its operation has been taken into account in the instructions. These recommendations are crucial, as improper use of air purifiers may lead to increased exposure and consequently a higher risk of illness.

The selection, sizing, and correct use of air purifiers require a broad understanding of both health factors and technical solutions. This includes among others the following topics:

Factors that increase the risk of illnesses and symptoms

- Routes of exposure to the body (e.g. respiratory system and skin)
- Factors influencing the reduction of illness risk
- Disease transmission methods (contact, droplets, and airborne transmission)
- The significance of cumulative exposure
- The impact of ventilation, air purifiers, and protective equipment on illness risk
- Different air purification techniques, their effectiveness and proper use
- Who should be particularly protected and when health protection is economically reasonable

Exposure refers to indoor air pollutants, such as human-derived viruses and bacteria, environmental microbes, various fine particles, fibers, allergens, chemicals, and harmful gases. The most common routes through which these pollutants enter the body are the respiratory system, skin, eyes, and digestive system. (Feld-Cook & Weisel, 2021)

Disease transmission can occur through contact, droplets, or airborne pathways. Contact transmission can be prevented by hand hygiene and the use of protective equipment, while airborne transmission can be reduced through effective ventilation and air purifiers. (Morawska *et al*., 2020)

Environmental exposures can increase the risk of illness. Environmental pollutants, such as industrial and building material fibers or harmful chemicals, can strain the respiratory mucous membranes and increase the risk of illness. The

mucous membranes serve as the body's first line of defense, preventing harmful substances and microorganisms from entering the body. When these mucous membranes are damaged by sharp fibers or particles, their protective function can weaken. Through damaged mucous membranes, microbes, such as viruses and bacteria, can more easily enter the body, increasing the likelihood of illness. (Huff *et al*., 2019; Sapuan & Ilyas, 2022)

Air purification helps maintain healthy mucous membranes by reducing overall exposure. It removes both pathogens and other harmful pollutants, such as fibers and chemicals, from the air. When the amount of pollutants decreases, the mucous membranes retain their protective function better, and the risk of illness decreases. (Huff *et al*., 2019; Schichlein *et al*., 2023)

People can spread significant amounts of pollutants, such as bacteria- and virus-laden droplets, around them by coughing, sneezing, or talking. A single sneeze may contain up to 40 000 droplets and 100,000 bacteria, and these pollutants can spread over a wide area depending on the size of the droplets and room ventilation. According to one study, droplets travel six meters when sneezing, two meters when coughing, and one meter when breathing. (Xie *et al*., 2007)

Droplets larger than 10 micrometers cannot remain airborne but quickly settle on surfaces, meaning they pose a risk of infection in close contact. Droplets and particles smaller than 5 micrometers can remain airborne for long periods and be carried by air currents from one area to another, posing a risk of infection over a wider area. (Xie *et al*., 2007)

Particles smaller than 2.5 micrometers are particularly significant because they can travel deep into the lungs, and particles smaller than 0,1 micrometer can even enter the bloodstream and other organs via the lungs. (Nikodinovska & Mladenovska, 2015)

The spread of droplets and particles and their impact largely depend on how air currents move within a space. In poorly ventilated rooms, small particles can remain airborne for several hours, and the longer they remain in the air, the greater the risk for others to inhale them and become exposed to pathogens. (Qian & Zheng, 2018)

The risk of transmission is influenced by factors such as the lifespan of the microbes in the environment, the number of microbes, and the distance between the infected person and the exposed person. (Wei & Li, 2016)

The lifespan of a microbe depends on its type and the physical properties of the environment. Most viruses and bacteria remain infectious for minutes or hours outside the body. Dry and cold air, for example, extends the lifespan of e.g. influenza viruses. After a cough, a 20 µm droplet containing the influenza virus dries in +20°C within a second to half of its original size, causing the salt in the droplets to crystallize, rendering the virus inactive. (Lounamo *et al*., 2014)

The likelihood of infection is proportional to how close the exposed person is to the infected person. For example, in airplanes where people sit in rows, the number of microbes decreases rapidly as the distance from the infected person

increases. Two meters away from the infected person, there are up to 500 times more microbes than at thirty meters away. (Rydock, 2004)

Air purifiers help reduce the number of airborne pollutants. By reducing both large and small pollutants, such as viruses and harmful fibers, air purifiers significantly lower the risk of illness by reducing exposure to microbes. Air purification is especially important in spaces where people spend long periods, as it helps keep the air clean and prevents microbes from spreading over a wide area. (Morawska *et al*., 2020)

Cumulative transmission risk increases the likelihood of illness. The risk of illness is directly proportional to the number of microbes entering the human body. Cumulative exposure means that both many microbes in a short time and a smaller number of microbes over a slightly longer time can lead to illness.

Doubling the concentration of pollutants in the air significantly increases the risk of illness. On the other hand, the larger the number of microbes a person is exposed to, the more severely the person typically becomes ill. For example, it takes only 1-30 viruses to cause an influenza infection. The assumption is that 30 viruses cause more severe symptoms than 1 virus. (Bosis *et al*., 2008, Franz *et al*., 2010; Li *et al*., 2010)

Good ventilation halves the amount of exposure. With ventilation that complies with regulations, where air is exchanged at least once every two hours (ventilation rate of 0.5 1/h), indoor air pollutants can be reduced by approximately half. However, this requires that the incoming air is filtered, there are no significant sources of exposure inside the building, the replacement air is clean, and the ventilation system is of a mixing type. (Qian & Zheng, 2018)

If the space contains sick individuals or carriers of disease, the importance of ventilation and air purification becomes more pronounced. Coughing, sneezing, and even breathing can release significant amounts of pathogens into the air, which can remain airborne for a long time. In such cases, in addition to ventilation, air purifiers with a high Clean Air Delivery Rate (CADR) are needed to effectively remove both pollutants and pathogens. (Huff *et al*., 2019; Schichlein *et al.*, 2023)

An air purifier reduces pollutants. The primary function of air purifiers is to remove impurities from the air, such as microbes, dust, allergens, and harmful chemicals. The performance of an air purifier is affected by its CADR value, which indicates how much clean air the device can produce per hour. The higher the CADR value, the faster and more efficiently the device reduces the amount of exposure in the room. For example, H13 filters according to the EN1822 standard remove at least 99.95% of airborne particles, making them particularly effective in combating pathogens. (Obitkova, 2024)

There are two main types of air purification exhaust techniques: mixing and laminar airflow. Laminar flow is a unidirectional and low-turbulence air distribution method. (Guangyu *et al.*, 2019)

The mixing technique evenly mixes the purified air with the room air, gradually reducing the concentration of contaminants. The higher the CADR value of the device, the faster this process occurs. (Qian & Zheng, 2018)

The mixing technique is most beneficial when there is a need to purify the air throughout the entire space, such as in schools, kindergartens, buildings with indoor air problems, or environments with a large number of sick individuals. (Li *et al*., 2010)

Laminar flow air purifiers provide a more efficient solution, especially when a specific area needs to be protected with highly purified air. In laminar flow, the airflow moves typically vertically at 0.3 m/s from an H13 filter with 99.95% purity. The purified air flows in a specific direction, creating a clean air zone where the purified air does not mix with contaminated air. This is crucial in areas where extremely clean air is required in a confined space. (Sparks & Chase, 2016)

Laminar flow air purifiers can easily reduce exposure levels to one-twentieth, as the clean air zone quickly displaces contaminated air in just a few seconds. Additionally, this is achieved with relatively small amounts of air and energy consumption. Highly efficient air purification in the breathing zone significantly protects against illness, even if there is a sick person in the same room and/or if the person being protected has a weakened immune system. (Sparks & Chase, 2016)

The greatest benefit of laminar flow is achieved when there is:

1. A need for a local clean zone at a workstation (e.g., a single person in a large space, where the protected area is moderately small and there are few disruptive airflows)
2. A need for exceptional protection (e.g., for someone with a weakened immune system or in an environment with poor air quality)
3. A need for exceptionally low noise levels and/or energy consumption (e.g., work that requires concentration)

Certain groups of people, such as those with weakened immune systems or individuals frequently exposed to sick people in their jobs (e.g., cashiers and reception workers), particularly benefit from air purification. Cancer patients, those sensitive to environmental factors, and people under long-term stress can also benefit from air purifiers, as they are more susceptible to illness. (EPA, 2024)

7.6.2 Discussion and conclusions

This article aims to highlight, at a general level, the key factors that can significantly reduce illnesses with the help of air purifiers and ventilation.

Publicly funded air purifier studies have often provided conflicting information about the effectiveness of the devices. There are numerous pitfalls in the use of air purifiers. If all of these are not taken into account, the benefits may easily go unnoticed in studies. In many studies, it is evident that not all factors have been adequately considered. In the E3 studies, both technical and health related aspects were taken well into account, and air purifiers were shown to reduce sick leave in daycare centers by 18%, which is an excellent result.

The mixing air purifier technique is chosen when an effect is needed over the entire room. The laminar technique is best when highly effective protection is required in a small area. With the laminar technique, exposure can be reduced to

one-twentieth, significantly lowering the rate of illness. Air purification is cost-effective for employees who have between 6 to 17 sick days per year and are at higher risk of illness.

There are also limitations and risks associated with air purifiers:

- Standard (mixing) air purifiers can cause significant secondary airflows. In cases where the cleaning capacity is too low relative to the need, they can spread pathogens and worsen the situation.
- Airflow directed from the sick to the healthy increases the risk of illness. This airflow can be caused by either the air purifier or the ventilation system.
- Some air purification techniques, such as ozone generation, ionization, certain plasma and uv-purifiers, and electrostatic filtration, increase the risk of producing highly harmful oxygen radicals or ozone. These increase oxidative stress and can damage mucous membranes or cause lung infections.
- The filter bypass of commercial quality air purifiers reduces filtration efficiency.
- Inadequate maintenance or an improperly installed filter can significantly reduce efficiency.
- Insufficient purification capacity can create an unfounded expectation of the device's effectiveness.
- Strong disruptive airflows can direct clean air to the wrong place, meaning the clean air does not adequately protect the room’s occupants.
- Selecting air purifiers and purification techniques, determining the purification capacity, calculating it, and positioning air purifiers require high expertise to achieve an excellent and economically viable result.

Health protection may be economically beneficial. One significant advantage of using air purifiers is their ability to improve staff health and well-being by reducing illnesses. By effectively removing pathogens and other harmful particles from the air, exposure is reduced, which lowers the risk of illness and sick leaves. This directly impacts employee health and productivity: the fewer illnesses, the fewer sick days, and the smoother the work process. Economically, this means that the investment in air purifiers can pay off by reducing sick leaves and increasing productivity. For example:

- Typically, the cost of one sick day is around €350–450.
- The cost of renting air purifiers is often €400-1200 per person per year, equivalent to the cost of 1-3 sick days.
- Air purification reduced sickness by 18% in a study conducted in Helsinki daycare centers.
- Thus, the economic benefit outweighs the cost for employees who take 6-17 sick days per year and are more susceptible to illness.
- Additionally, improved work performance is often a benefit.

Considering all the limitations and pitfalls, it is recommended to use the highest quality devices, with the best ones designed as dual-purpose products. Among the devices used in this study, the ISEC air purifiers were dual-purpose devices. This

means that they can be used not only for daily air purification but also in critical emergency situations, such as during chemical, biological, radiological, or nuclear (CBRN) incidents. The purifiers are designed to be quickly adapted to respond to such serious threats when necessary additional measures and modifications are implemented. This makes them especially valuable in places such as healthcare facilities, public spaces, and government buildings, where civil protection and preparedness for crisis situations are key concerns.

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8 Clean air production in hospital environment

8.1 The importance of indoor air quality in hospital environment

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Abstract: The studies in this chapter explore the importance of indoor air quality (IAQ) in response to the COVID-19 pandemic, focusing on the behaviour of air particle pollution in healthcare environments. The motivation behind the research was driven by the need to find effective pandemic response strategies. Multidisciplinary research was carried out in various hospital buildings, involving air quality measurements, portable air purifier interventions, surveys, simulations, and infection risk assessments.

8.1.1 Introduction

The COVID-19 pandemic, alongside other health crises, has drawn our attention to the critical importance of health and well-being, resilience in society, and the potential detrimental impact on global economics (Fernández-Agüera et al., 2022). To sustain our defences against future pandemics, a comprehensive understanding of virus behaviour in various environments, especially healthcare facilities, is fundamental. Effective pandemic response strategies involve a multidisciplinary approach, implying collaboration between medical professionals and industry experts. E3 multidisciplinary research provided research-based knowledge and technology development support for proof-of-concept testing. The proof-of-concept experimental research was conducted in three different hospital buildings in Finland and Romania. The research methods included user surveys, indoor and outdoor air quality measurements, indoor air flow simulations, and infection risk and indoor air quality assessments. This paper gives an introductory overview of the subject and

the main conclusions of the research, which are presented in more detail in the following papers of the chapter.

8.1.2 Background

Mechanical ventilation systems play a vital role in ensuring a healthy and safe environment within hospital buildings (Shajahan et al., 2019). Initially, mechanical ventilation systems were designed to offer a consistent supply of fresh air while regulating temperature, humidity, and air pressure levels. However, as ventilation technology has advanced and air filtration technology has emerged, additional functions have been assigned to these systems. These include air filtration to prevent the spread of airborne viruses, as well as the removal of stale air, dust, and other contaminants (Olsson, 2017).

The emergence of the COVID-19 pandemic in 2019, which has tragically resulted in the loss of 7,010,681 lives as of April 13, 2024, has underscored the critical importance of managing and reducing infection risks within enclosed spaces, particularly in hospital buildings (Coronavirus Cases, 2024). This is necessary not only to prevent the transmission of COVID-19 among patients but also to safeguard the healthcare personnel responsible for patient care.

The E3 project's goal was to harness modern science and technology to create effective countermeasures to prevent the spreading of novel infectious diseases. Through the implementation of indoor air quality (IAQ) measurement campaigns within hospital facilities, the primary aim of this research is to highlight the benefits of integrating mechanical ventilation systems and state-of-the-art air purification technologies in hospital buildings. This integration serves the purpose of sustaining a wholesome indoor air environment and diminishing the potential risk of airborne infections. This is accomplished by conducting field measurements of indoor air parameters, which serve as proxies for evaluating air quality and calculating infection risk (Satheesan et al., 2020). The measurements were conducted in three different hospital buildings, each equipped with a distinct ventilation system: a naturally ventilated hospital in Romania, a hospital in Helsinki, Finland equipped with an advanced modern ventilation system, and a hospital in Espoo, Finland with traditional mechanical ventilation. The data obtained from these measurements were used to develop an IAQ model, enabling the evaluation of IAQ and infection risks in various scenarios.

8.1.3 Aim and research questions

The objective of use case one (UC1) of the E3 project was to have a best practice technologies recommendation for clean air production to maintain IAQ and prevent pathogen spread in in hospital buildings. This objective was achieved by comparing IAQ measurement results from different hospital buildings with different clean air production (ventilation systems, air cleaners) and concluding the results with the findings from the personnel interviews.

Research aim

The aim of this UC1 was the following:

- to gather on-site measurements for key parameters that signify good IAQ.
- to study the potential benefits of using air purification systems in three different spaces (two patient rooms and waiting area) in each studied hospital building by comparing IAQ parameters before and after using the air purification systems (three different hospital environments with different kinds of ventilation systems).
- to understand possible air spread pathogens pathways between patient rooms and corridors through studying functions of mechanical ventilations system and air flow between spaces.
- to identify important factors in the interaction between people and indoor air as well as air purification systems affecting the user experience with the air purification.

Research questions

The research tried to answer the following questions

1. How does the current mechanical ventilation system installed in the investigated case studies perform?
2. Can infectious aerosols be shown outside patient rooms?
3. What is the reduction ratio of fine PM emissions in the indoor air before and after the intervention of an air purification system?
4. How much infection risk may be reduced with clean air production based on indoor measures and simulation-based infection risk analyses?

8.1.4 Research design

This experimental research was designed to evaluate IAQ and infection risks within hospital environments by assessing the performance of different ventilation systems. The methodology consisted of two primary phases as follows:

1. Ventilation System Auditing

The first phase involved a detailed audit of the ventilation systems in the selected hospital spaces. This included measuring airflows and pressure differences to assess the efficiency and operational characteristics of each ventilation system.

2. Measurement Campaign

A one-week measurement campaign was conducted to collect data on key IAQ parameters (Figure 1). The following parameters were measured to evaluate air quality and potential health risks: Particulate matter ($PM_{2.5}$), lung-deposited surface area (LDSA), total volatile organic compounds (TVOC), black carbon (BC) concentrations, CO_2 concentration, air temperature (T), and relative humidity (RH%). The data collected served as the foundation for constructing IAQ models

and analysing the potential risks of airborne virus transmission within hospital settings.

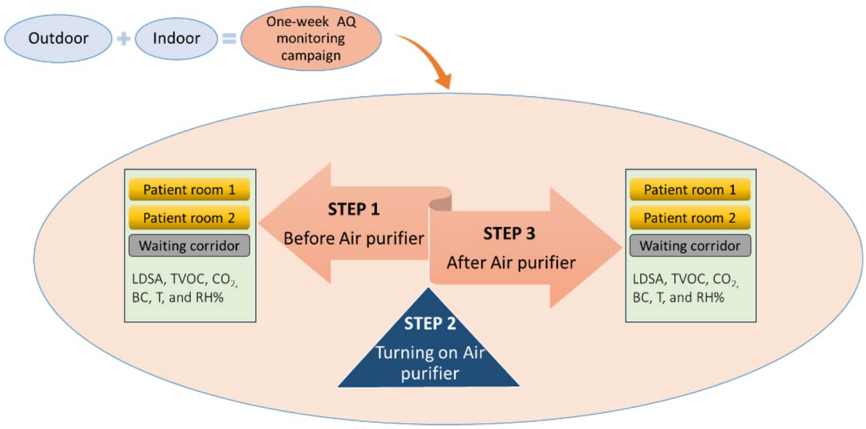

Figure 1 Monitoring campaign steps diagram

8.1.5 Results

- The preliminary study found that implementing air purifiers in hospital patient rooms with natural ventilation significantly lowered $PM_{2.5}$ indoor-outdoor (I/O) ratios by 78% - 93%. A similar reduction of 36% - 58% was observed in patient rooms of mechanically ventilated hospital buildings.

- In the investigated case studies, indoor particle concentration is influenced by both outdoor and indoor sources.

- Using portable air cleaners with HEPA filters mechanically ventilated hospital buildings could help meet isolation room design requirements for total air change hours (ACH).

- Indoor air quality is influenced by geographical location, building characteristics, ventilation systems, and indoor activities

- The advantages of using portable air purifiers are particularly pronounced in highly polluted environments.

- The findings from the infection risk assessment highlight the considerable potential infection probability reduction benefits associated with the implementation of portable air purifiers featuring HEPA filters in both naturally and mechanically ventilated hospital buildings.

8.1.6 Acknowledgements

The authors extend their heartfelt gratitude to the Hospital team in Romania and Finland for their invaluable cooperation.

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8.2 The influence of using portable air purifiers on the PM2.5 concentration in hospital patient rooms in a hospital building in Finland

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Abstract: Following the COVID-19 pandemic, there remains a knowledge gap regarding air quality (AQ) in patient rooms. A one-week measurement campaign was conducted in a Finnish hospital to assess particulate matter (PM) concentrations in four isolation rooms. Air purifiers were utilized in two of the rooms. The results showed a 37% to 56% reduction in $PM_{2.5}$ indoor/outdoor (I/O) ratios with the use of air purifiers, highlighting their effectiveness in improving indoor air quality (IAQ) and reducing airborne infection risks.

8.2.1 Introduction

Mechanical ventilation systems are crucial for maintaining a healthy and safe environment in hospitals buildings. Unlike natural ventilation, mechanical ventilation systems are designed to provide a sufficient fresh air and maintain a regulated temperature, humidity, and air pressure. These systems have evolved with advancements in ventilation and air filtration technology. In addition, mechanical ventilation systems perform functions, such as filtering air to prevent the spread of airborne viruses and removing particulate matters (PM) pollution (Nourozi et al., 2023). PM pollution in a hospital environment can originate from outdoor and indoor sources. Outdoor PM may enter indoor spaces through open doors or windows, leaks in the building envelope, or the ventilation system. Conversely, indoor PM sources in a hospital environment include various human activities and localized sources of PM, such as the use of cleaning agents, medical procedures, construction and renovation materials, and even the materials of furniture and flooring (Chamseddine and El-Fadel, 2015).

Previous studies have shown a strong correlation between indoor and outdoor PM mass concentrations in hospital buildings (Morawska, 1998), implying that outdoor PM influences indoor PM levels in the hospitals under investigation (Lomboy et al., 2015) However, advanced filtration and ventilation systems are more effective at reducing overall PM concentrations from outdoor sources in hospital buildings than in buildings with traditional ventilation systems (Morawska, 1998). The study aimed to improve understanding of airborne particles and aerosols characteristics in mechanically ventilated hospital isolation rooms. Its specific goals were to: (1) continuously measure outdoor and indoor $PM_{2.5}$ levels in four isolation

rooms; (2) assess the impact of portable air purifiers on PM concentrations in two of these rooms; (3) evaluate airborne infection risks in ventilated healthcare facilities; and (4) create solutions for reducing infection risks through effective ventilation and air purification strategies

8.2.2 Methods

Case study description

For this study, four isolation rooms were selected from a hospital in Espoo, Finland. The hospital building was equiped with a constant air volume (CAV) ventilation system[7]. The investigated rooms were located on the fifth floor and featured a central service core surrounded by a corridor that connects all patient rooms on both sides (see Figure 1). The selected rooms (3-6) are located on the east side of the building, each with a surface area of approximately 15 m².

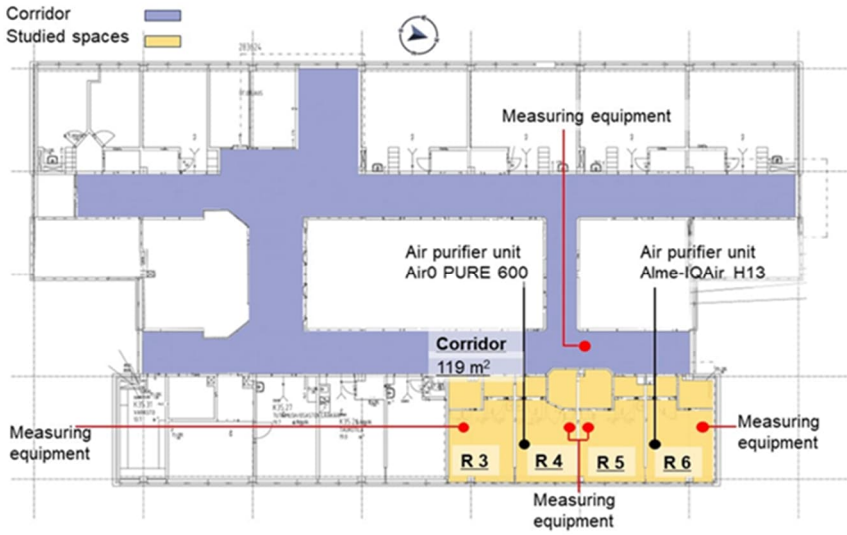

Figure 27. Investigated rooms 3,4,5, and 6.

The measurement campaign, carried out from September 22nd to 30th, 2023, included all four rooms. Portable air purifiers were utilised in two rooms (rooms 4 and 5). Each room had two supply air outlets and three return air inlets. The supply outlets served both the anteroom and the main room, while the return inlets drew air from the anteroom, toilet, and main room. Following Finnish regulations for

[7] A Constant Air Volume (CAV) ventilation system is a type of HVAC (Heating, Ventilation, and Air Conditioning) system that maintains a constant airflow rate and adjusts the temperature of air to meet the desired condition.

isolation room design, all rooms were designed to maintain negative pressure (NIH, 2021).

Indoor and outdoor measurements

The indoor air quality was quantitatively evaluated by measuring the $PM_{2.5}$ mass concentrations in all four rooms (3-6). A miniaturized optical particle counter (OPC-N3 from Alpha sense) was used for the $PM_{2.5}$ mass concentration measurement (1 second resolution). The indoor OPCs were attached to a tripod at a standardized height of 150 cm, and the tripod was positioned near the patient's bed. The outdoor OPC sensor was placed at the primary intake point of the main HVAC handling unit and was carefully protected from outdoor weather conditions. The measurement method follows the guidelines for the quantitative measurement of airborne endotoxins by the European standard EN 481. Before starting the measurement campaign, a comprehensive sensors testing procedure was made at VTT-Technical Research Centre of Finland

Before implementing the air purifier interventions in Rooms 4 and 6, both supply and exhaust airflow were measured by Granlund consultants using a portable digital ventilation meter. These measurements were conducted to plan the optimal configuration for the air purifier units. In Room 4, an Air 0 PURE600 air purifier unit with a Clean Air Delivery Rate (CADR) of 640 m^3/h, featuring HEPA and activated carbon filters, was used. In Room 6, a Sandbox Group IQ Air H13 air purifier unit with a CADR of 530 m^3/h, equipped with an F8 pre-filter and H13 HEPA filter, was installed. The airflow data, along with other measured parameters, were used to calculate infection risk using the Wells-Riley model, which is commonly applied in ventilation design and indoor air quality studies, especially for estimating airborne infection risks (Noakes and Sleigh, 2008).

8.2.3 Results

Throughout the monitoring period and for most of the time, the indoor $PM_{2.5}$ mass concentration remained lower than the outdoor concentration, and under the WHO global air quality guidelines (i.e., 24-hour average concentration of 15 $\mu g/m^3$) (WHO, 2021). However, short spikes in concentration in rooms 4 and 6 were noticed, reaching 30-minute average concentrations of up to 200 $\mu g/m^3$ (see -Figure 2). The cause for these spikes, however, was not in-depth investigated. Nevertheless, certain peaks coincided with instances of door opening. The efficiency of the portable air purifiers in minimizing indoor particle concentration were evaluated by calculating the ratio of the indoor to outdoor (I/O) $PM_{2.5}$ concentrations. After turning on the air purifiers, a reduction of 58 % and 36 % were observed in the median I/O ratio in rooms 4 and 6, respectively.

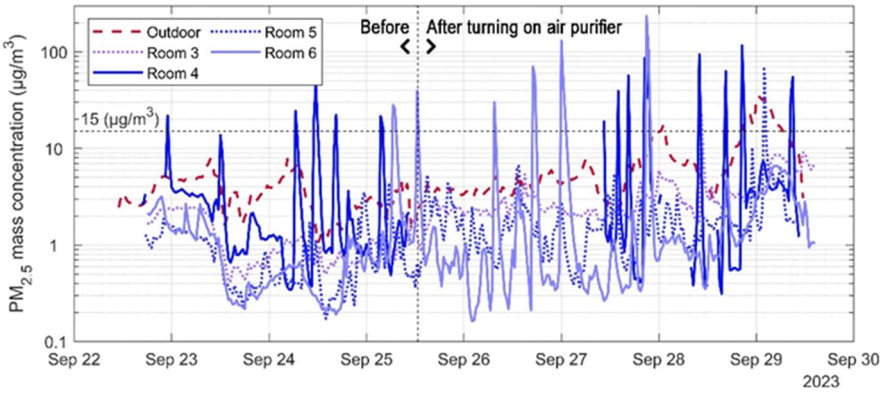

Figure 28. $PM_{2.5}$ mass concentration time series. The horizontal dotted line marks the WHO guideline value of 15 µg/m^3 (24-hour average) and the vertical dotted line marks the time when air purifiers were installed in the patient rooms.

The airflow measurements conducted prior to the monitoring campaign revealed a significant deviation from the designed supply airflow rates. The utilization of portable air purifiers in rooms 4 and 6, with air changes per hour (ACH) ranging from 9 to 7.8, theoretically led to an indoor ACH increase from the measured flow of 1.7 - 2 to 10.7 to 9.8, for rooms 4 and 6, respectively. These new values met the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) guidelines for portable air purifier design. While the fan in a portable air purifier does not increase ACH directly, it can improve air circulation and distribution, which supports better air quality and can complement the effectiveness of the room's ventilation system.

The results from the infection risk calculations indicate that the probability of infection decreases significantly after utilizing the air purifier units. For example, in Room 4, with a design value of 4 ACH, the infection probability was lower by 50% than the initial measured conditions of 1.7 ACH over a period of 24 hours. The implementation of air purification with an ACH of 9 decreases the probability of infection by a factor of 3.5 compared to without air purification. In all examined scenarios, the combination of mechanical ventilation (with a proper ACH value) and an air purifier demonstrates efficiency in reducing infection risk probability, even in instances characterized by high quanta emission rates[8] (Bongalo, 2004).

[8] Quanta emission rates refer to the rate at which airborne infectious particles, or "quanta," are released into the air from a source, such as an infected individual or a contaminated surface.

8.2.4 Discussion and conclusions

The reduction in $PM_{2.5}$ mass concentration after using the purifiers highlights the potential advantages of employing portable air purifiers for mitigating aerosol transmission, thereby reducing the risk of infection among hospital occupants. Our investigation revealed that indoor particle concentrations within the examined patient rooms were influenced by indoor activities and outdoor particle concentration. The findings from the infection risk assessment highlight the considerable potential infection probability reduction benefits associated with the implementation of portable air purifiers featuring HEPA filters in mechanically ventilated hospital buildings. This proactive measure not only has the potential to reduce the risk of infection but also meets the design requirements for total air changes per hour (ACH) in isolation rooms

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8.3 The influence of using portable air purifiers on the $PM_{2.5}$ concentration in naturally ventilated hospital patient rooms in Romania

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Abstract: This study assessed the effectiveness of portable air purifiers in reducing particulate matter ($PM_{2.5}$) concentrations in naturally ventilated hospital rooms. Measurements in two patient rooms over one week showed a $PM_{2.5}$ reduction of 78%-93% after using the purifiers. The results suggest that portable air purifiers with HEPA filters can enhance air quality and reduce infection risks, improving safety for patients and healthcare workers.

8.3.1 Introduction

Maintaining indoor air quality (IAQ) is vital for the health and well-being of healthcare facilities' occupants. Traditionally hospital buildings have relied on natural ventilation to provide fresh air for occupants (Jung et al., 2015). However, this approach is often ineffective in situations where controlling the indoor environment, and the spread of pathogens, is crucial (Gilkeson et al., 2013). Advanced mechanical ventilation and filtration systems are utilised to provide maintained fresh and clean indoor air. However, existing, and old hospitals face challenges in installing these systems due to technical and financial issues.

Over the last 30 years (i.e., 1990-2020), the construction of new hospitals in the public sector in Romania has been very rare. Instead, reliance has been placed on existing and old hospital buildings, the majority of which rely solely on natural ventilation. In this context, portable air purifiers have been introduced to existing and old hospital buildings as a solution for improving IAQ. Air purifiers have been developed to capture small particles such as particulate matter ($PM_{2.5}$), which could cause various respiratory diseases and have a higher likelihood of carrying viruses.

The aim of this research was to investigate the advantages of using portable air purifiers in traditional naturally ventilated hospital building. A one-week measurement campaign was conducted in two patient rooms in a naturally ventilated hospital building in Bucharest—an ICU room and an isolation room. The campaign investigated $PM_{2.5}$ concentrations before and after using portable air purifier units. Additionally, other aspects of indoor environmental quality parameters, such as: CO_2 levels, temperature, and relative humidity were monitored. Measured parameters values were used for infection risk calculation.

8.3.2 Method

Two patient rooms in two buildings were selected for the study-an ICU room, and an isolation room. Both buildings were built at the beginning of the 1900 era, featuring concrete construction and brick walls. The buildings were naturally ventilated through windows and doors, and exhaust air being removed through exhaust shafts. The ICU room (25.38m^2) was located on the second floor of a four-story building and faced north (see-Figure 1). The isolation room (13.60m^2) was located on the second floor of the four-story isolation ward building and faced east (see Figure 2).

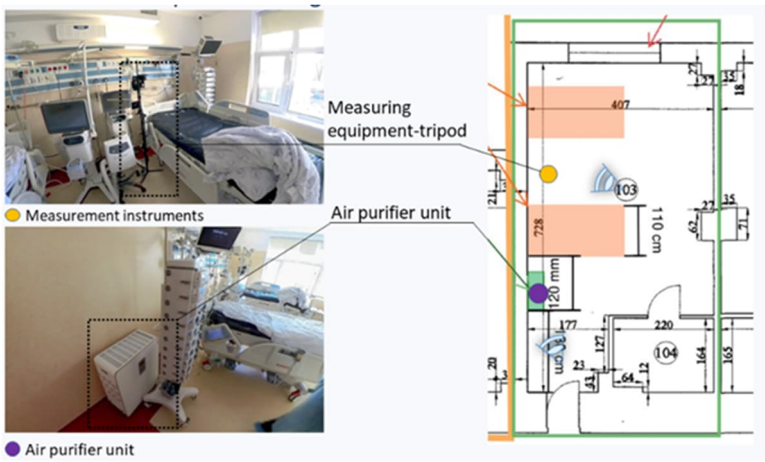

Figure 29. Indoor sensors and air purifier placement - ICU room

The particulate matter concentrations ($PM_{2.5}$) as well as other indoor environmental quality parameters were measured in both rooms over a period of one week (13-17 February 2023). For the $PM_{2.5}$ measurement, a miniaturized optical particle counter (OPC-N3 from Alphasense) was used for the measurement. For other parameters, HOBO data loggers MX1102 were utilised. For indoor measurement, sensors were attached to a tripod in each room at different heights: one OPC sensor at the height of 150cm, and HOBO sensors at the height of 150, 100, and 50 cm. For the outdoor measurements, an OPC and HOBO sensors were positioned on the second-floor balcony on the western side of the isolation department building. Outdoor sensors were positioned within a designated outdoor enclosure to protect them from weather conditions.

Two portable air purifiers (Kuulas+ from ISEC) were utilised for the study. Each air purifier unit was outfitted with three distinct filters: a coarse filter to eliminate sizable dust particles, an active carbon filter to reduce the concentration of chemical and gaseous compounds in the air, and a HEPA filter, demonstrating efficacy in removing 99.97% of dust and pollen particles with a size exceeding 0.3 µm (ISEC, n.d.). In both rooms, the air purifier was placed next to the patient bed, operating at

60% power, and delivering CADR of 192m^3/h. To investigate the impact of the utilisation of air purifiers on indoor $PM_{2.5}$ concentrations, the indoor/outdoor (I/O) $PM_{2.5}$ ratio was calculated before and after using the air purifiers. The infection risk probability was calculated by using the Wells-Riley model, using quanta emission rates as an indicator of infection doses that influence the infection transmission probabilities. The calculations considered the air purifiers settings, and some aspects of the measured parameters.

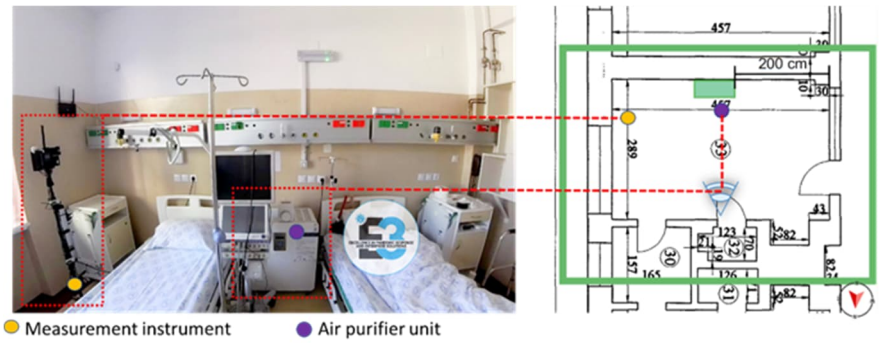

Figure 30. Indoor sensors and air purifier placement-Isolation room.

8.3.3 Results

In the isolation room, the $PM_{2.5}$ concentrations during the whole monitoring period were lower than the outdoor $PM_{2.5}$ concentration and within the World Health Organization (WHO) global recommend value for air quality guidelines (i.e., a 24-hour average concentration of 15 µg/m^3) (WHO, 2021), turning on the air purifier contributed to further decrease in the $PM_{2.5}$ concentrations reaching the lowest value of 1.0 µg/m^3 (see-Figure 3). In the ICU room, the $PM_{2.5}$ mass concentration was close to the recommended WHO value however, there were some spikes before and after turning on the air purifier. Both average $PM_{2.5}$ concentrations, and the spikes were lower after turning on the air purifier compared to prior the use of the air purifier unit.

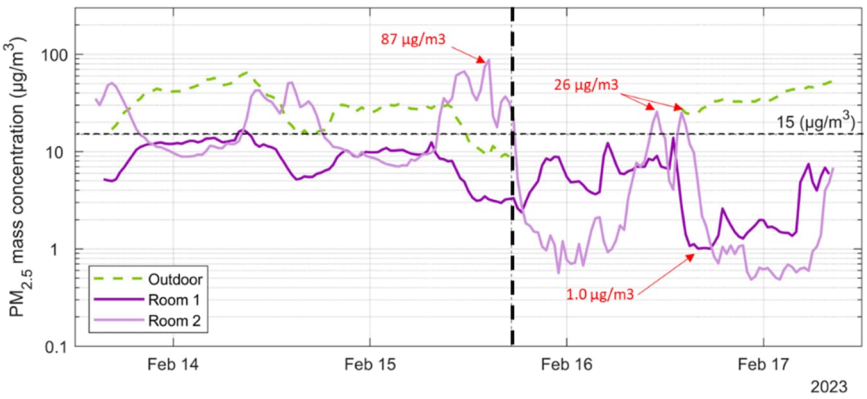

Figure 31. $PM_{2.5}$ mass concentration time series. The vertical dotted line represents the time when air purifiers were turned on and the horizontal dotted line marks the WHO guideline value of 15 µg/m^3 (24-hour average).

The I/O $PM_{2.5}$ ratio was calculated before and after the implementation of the air purifier. In the isolation room (42m^3), there was a notable median reduction in the I/O ratio of 93%. Notable reduction was also noticed in the ICU room (78.7m^3) with a value of 78% (see-Figure 4). However, same air purifier units with the same settings were used in each room, various factors may have contributed to different $PM_{2.5}$ reduction values in the two rooms, such as room orientation, infiltration rate, and volume (Chen et al., 2022). The infection risk calculations revealed an increase of infection rates over the time if only natural ventilation was applied. However, the implementation of the portable air purifiers reduces the infection risk probability more than 50% from the original case for both rooms.

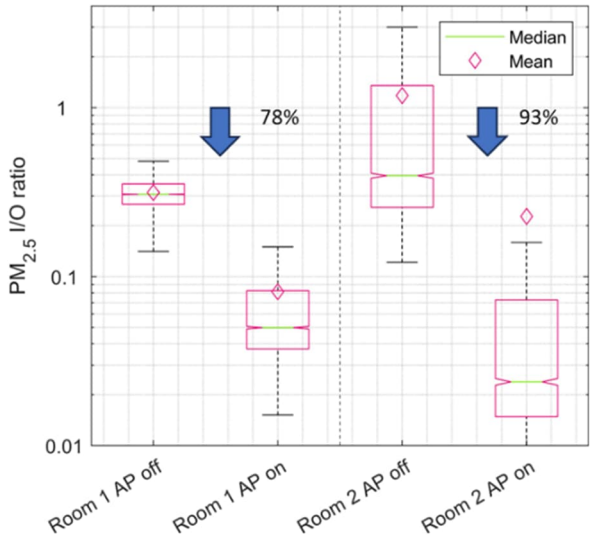

Figure 32. $PM_{2.5}$ mass concentration indoor to outdoor ratios - ICU, and isolation room.

8.3.4 Conclusions

The study aimed to investigate the potential benefits of using portable air purifiers in a naturally ventilated hospital building. The goal was achieved by measuring Particulate Matter ($PM_{2.5}$) concentration in two different patient rooms over a period of one week. The portable air purifier efficiency was evaluated by calculating the indoor/outdoor rations of $PM_{2.5}$ concentrations before and after using the air purifier unit. A reduction of 78%-93% was observed in the ICU room (78.7m³), and the isolation patient room (42m³) respectively. According to the infection risk assessment, with natural ventilation alone, and the lack of higher air change, the infection probability is the highest. The integration of air purifiers in both investigated the rooms halves the estimated infection probability. These findings highlight that using portable air purifiers with HEPA filters in naturally ventilated hospitals can supplement natural ventilation, lower the immediate risk of infection, and enhance indoor air quality, creating safer environments for patients and healthcare workers.

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8.4 Infection risk estimation in naturally ventilated patient room

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Abstract: Airborne infection control in naturally ventilated hospital rooms poses significant challenges, particularly in managing the spread of pathogens like SARS-CoV-2. This study explores infection risk in a COVID-19 ward and an ICU room using field data and dynamic simulations with IDA-ICE. The motivation is to assess the effectiveness of natural ventilation combined with air purifiers. Results show that natural ventilation alone is insufficient, especially at higher quanta emission rates, while the combination of air purifiers and controlled ventilation significantly reduces infection risk. These findings provide valuable insights for optimizing ventilation strategies in healthcare environments.

8.4.1 Introduction

The COVID-19 pandemic has underscored the importance of proper ventilation in controlling the spread of airborne diseases, especially in high-risk environments like healthcare facilities. Pathogens such as SARS-CoV-2 can remain viable in aerosols for extended periods, making efficient ventilation and air purification systems critical in hospitals to reduce infection risks (Fennelly et al., 2023). According to international standards, patient rooms should achieve between 4 and 12 air changes per hour (ACH) to effectively dilute airborne contaminants (Abbas and Dino, 2022). However, the limitations of natural ventilation, often used in older hospitals and buildings in warmer climates, have been exposed due to its inconsistent control over airflow (Gilkeson et al., 2013).

Despite these challenges, natural ventilation continues to be widely used in many hospitals, particularly in regions with warmer climates or older buildings designed to promote airflow through large windows, high ceilings, and cross-ventilation layouts (Fageha and Alaidroos, 2022). Retrofitting these facilities with modern mechanical ventilation systems is often difficult due to the significant structural changes required and the need to comply with contemporary regulations (Gilkeson et al., 2013). In such cases, a combination of strategies—including optimizing natural ventilation, using portable air purifiers, and introducing controlled ventilation in high-risk areas—may be necessary to improve indoor air quality (Moghadam et al., 2023).

Assessing infection risks in naturally ventilated hospital environments is complex, as it requires a thorough understanding of the physical dynamics of air distribution. These dynamics are influenced by fluctuating outdoor conditions, building geometry, and operational factors like window opening schedules. The

Wells-Riley model is widely used to estimate infection probabilities in indoor spaces, based on factors such as quanta emission rates, airflow, and room occupancy (Kurnitski et al., 2023). This model enables researchers and engineers to evaluate the effectiveness of different ventilation and air purification strategies in reducing the risk of airborne transmission.

This study focuses on assessing infection risks in two distinct patient rooms at the Matei Bals Institute for Infectious Diseases in Bucharest, Romania: a COVID ward and an Intensive Care Unit (ICU) room. This research fills a gap in existing studies, which have mainly focused on educational, commercial, and residential buildings (Moghadam et al., 2023). The findings of this study are expected to provide valuable insights for developing evidence-based strategies to manage infection risks in hospital environments that rely on natural ventilation and cannot be easily retrofitted with mechanical systems.

8.4.2 Case study

This case study examines the ventilation and air purification solutions in two hospital rooms at the Matei Bals Institute for Infectious Diseases in Bucharest, Romania: a COVID Ward and an Intensive Care Unit (ICU) room, each located in separate buildings within the hospital complex. The Matei Bals hospital building is constructed with traditional brick walls and large windows, which are typical architectural features of older healthcare facilities. Natural ventilation is the primary method for air exchange, with fresh air entering through openings and exhaust air expelled through a vertical shaft. In patient rooms, windows are opened every two hours to ensure fresh air circulation.

The preliminary survey provided critical insights into how the building was used, including the window opening schedule (every two hours for fifteen minutes) and general occupancy patterns. In the infection isolation rooms, staff wore protective suits and face masks to minimise exposure risks.

The COVID Ward is an isolated patient room with closed doors used for treating COVID-19 patients only. The is located on the second floor of a four-story building, designed for two patients (Figure 1). A closed hallway separates the patient rooms, with fresh outdoor air entering the room through infiltration and window openings, while exhaust air exits through the shaft. The room is heated by a water radiator placed under the window and connected to the district heating system. The preliminary survey of the COVID ward provided critical insights into how the building was used, including the window opening schedule (every two hours for fifteen minutes) and general occupancy patterns.

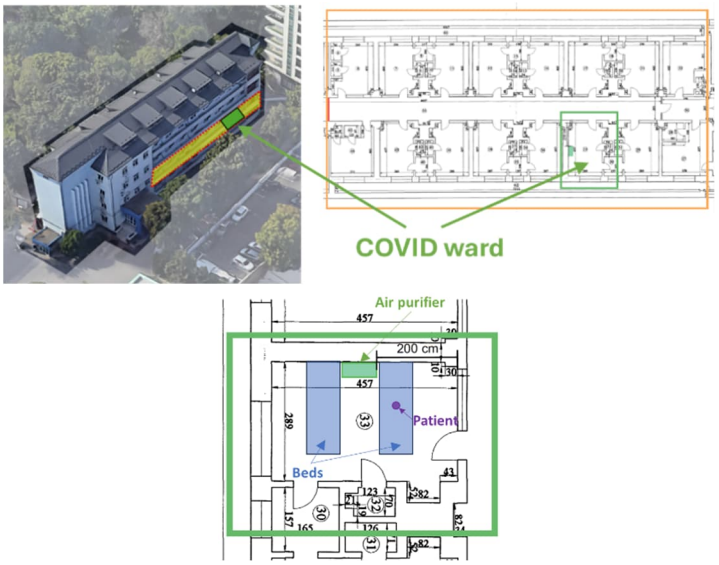


Figure 1. Location of Covid Ward in Matei Bals hospital building.

The ICU room, situated in a separate hospital building within the Matei Bals complex, treats critically ill patients and uses natural ventilation (Figure 2). In contrast to the Covid Ward, the ICU room features a fan coil unit for heating, located under the window and connected to the district heating system.

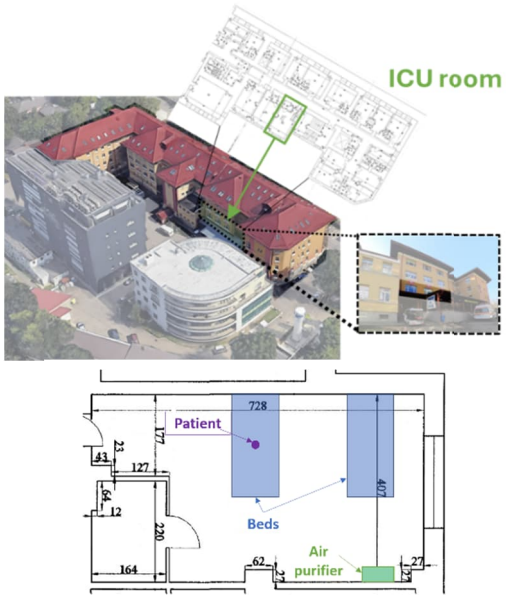


Figure 2. Location of ICU room in Matei Bals hospital building.

Portable air purifiers were installed during the case study to complement natural ventilation, and its effectiveness was evaluated using measurements and modelling techniques.

8.4.3 Methods

The methodology of this study follows an algorithm, beginning with a pre-study phase to gather initial data for simulations (Figure 3). This phase involved collecting architectural drawings, occupancy profiles (such as window opening schedules), and indoor air quality (IAQ) data through cloud-based monitoring. Additionally, key parameters for the infection risk model, such as quanta generation rates, breathing rates, and mask efficiencies, were predetermined based on literature and surveys.

Following the pre-study, dynamic building simulations were conducted using the IDA ICE software to calculate airflow rates, indoor temperature, and CO2 levels under varying ventilation strategies. These simulations accounted for room geometry, building envelope, and internal heat gains from lighting and equipment. The IDA ICE model used in this study has already been validated against real-world measurements in previous research, ensuring its accuracy for airflow and indoor air quality predictions in naturally ventilated patient rooms.

Once validated, the infection risk model, based on the Wells-Riley approach, was applied to estimate pathogen exposure under different ventilation scenarios.

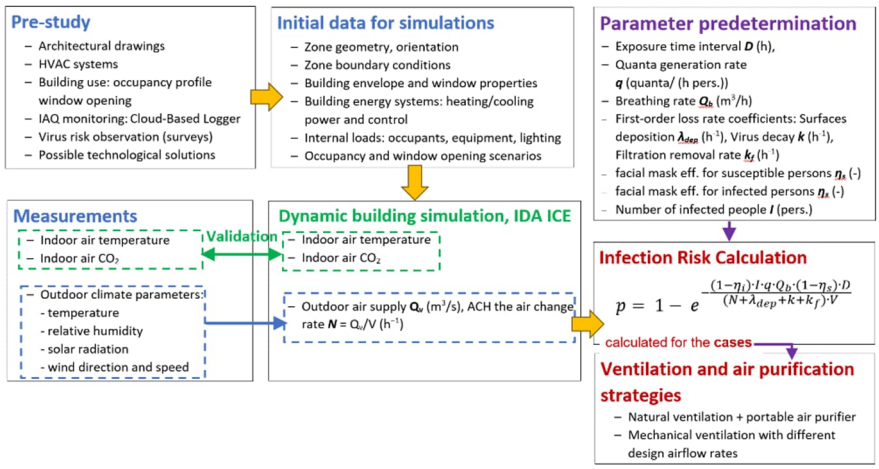


Figure 3. Infection risk calculation with building simulation techniques

8.4.4 Dynamic building simulation

This section describes the methodology for calculating dynamic airflow rates in naturally ventilated hospital rooms, focusing on both a COVID Ward room and an

ICU room. The aim was to evaluate air exchange rates and indoor air quality parameters using the IDA ICE building simulation tool.

The dynamic simulation model was set up with measured climate data from Bucharest to simulate outdoor conditions. Data from the pre-study campaign provided essential information such as room layout, outdoor climate parameters, and the characteristics of the building envelope. Visual observations were used to estimate parameters for the building envelope, exhaust shaft, and internal heat gains from lighting and equipment. For both rooms, air infiltration rates were calculated based on local wind conditions, building geometry, and pressure differences between indoor and outdoor air.

A key distinction in the simulation of the two rooms was the heating system: while the COVID Ward relied on a natural ventilation system with a water radiator for heating, the ICU room included a fan coil unit, which contributed to both heating and air circulation. The presence of the fan coil in the ICU room introduced additional complexity, as it affected air distribution and required more detailed airflow modeling compared to the simpler system in the COVID-19 ward.

In both simulations, the air purifier was modeled as a source of recirculating air and heat gain from equipment. A zone heat balance was calculated to maintain an indoor temperature of 21°C. Due to the difficulty in observing window operations in the hospital setting, window openings were excluded from the simulations, as their short duration had minimal impact on the indoor air measurements.

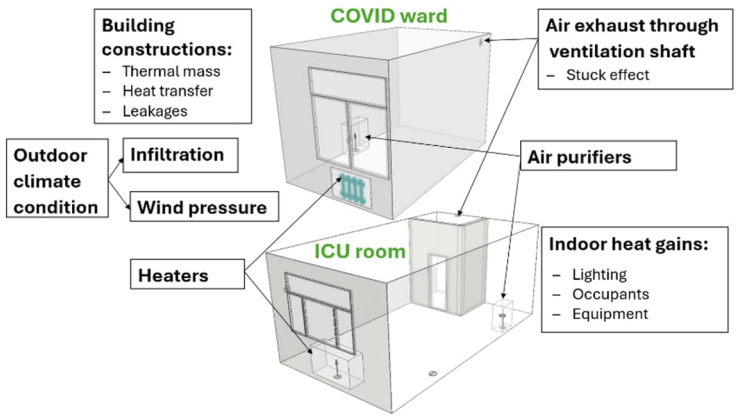


Figure 4. Initial values for dynamic simulation.

8.4.5 Infection risk calculations

Infection risk calculations were performed using the Wells-Riley model (Figure 3) a commonly applied model in ventilation design and indoor air quality studies to estimate the risk of infection transmission, particularly for respiratory diseases such as COVID-19 and influenza.

The parameters for the model were chosen based on the latest literature (Kurnitski et al., 2023). Due to the sensitivity of the Wells-Riley model to the quanta emission rate, the study analysed the impact of various emission rates on the probability of infection transmission in indoor spaces. The range of quanta emission rates used was from 2 to 10 quanta per hour per person (quanta/h pers), reflecting different levels of infectiousness (see Table 1). Simulations were performed under conditions where one infectious individual (I = 1) and one susceptible individual were present continuously. Both facial mask efficiencies for the infectious and susceptible persons ($\eta i = 0$ and $\eta s = 0$) were excluded from these calculations.

Table 1. Initial values for the infection risk calculations

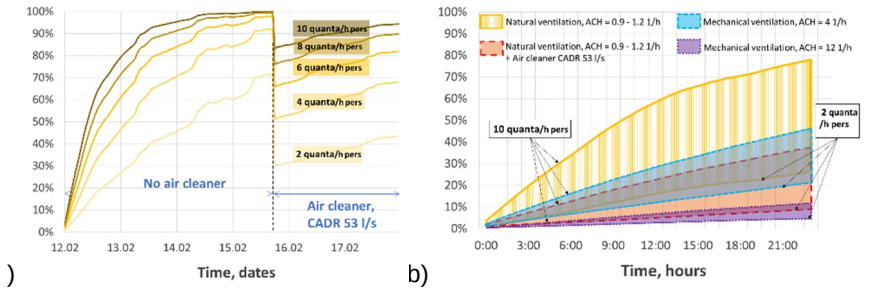
Parameter	**COVID-19 Ward**	**ICU room**
Floor area (m^2)	26.0	13.7
Height (m)	3.1	3.1
Volume (m^3)	80.6	42.3
Filtration rate by portable air cleaner k_f (1/h)	2.4	4.5

The effect of varying quanta emission rates between 2 and 10 quanta/h per person was also assessed across all scenarios to determine how different ventilation strategies and air purifiers impacted the infection risk. The following cases were evaluated to examine different ventilation and air purification strategies: natural ventilation without air purification, natural ventilation with a portable air purifier, mechanical ventilation with 4 ACH, mechanical ventilation with 12 ACH

8.4.6 Results

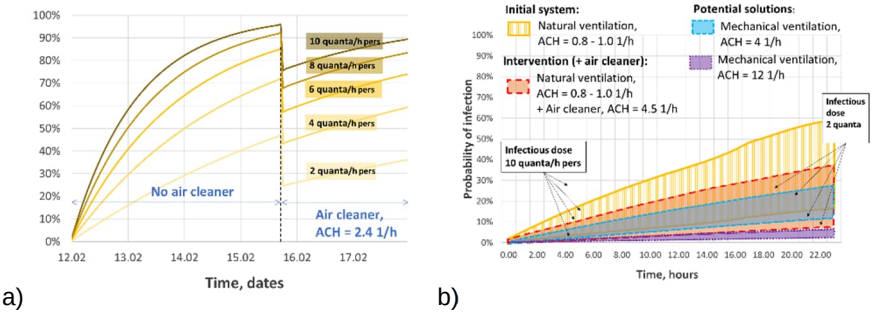
Infection probabilities were calculated both before and after air purifiers were installed in the patient rooms, as shown in Figure 5a for the COVID Ward and Figure 6a for the ICU room. The Wells-Riley model was used to estimate infection risks based on quanta emission rates, ventilation rates, room volume, and exposure time. It's important to note that while IDA ICE simulates airflow and temperature distribution, it does not directly model particle concentration. Therefore, the infection risk was estimated based on airflow rates and air exchange, assuming these would influence the dilution of airborne particles. nfection risk results show that with a lower quanta emission rate, such as 2 quanta/h per person, infection probability grows more slowly, and improvements in airflow, such as the use of air purifiers, significantly reduce the risk. However, with higher quanta emission rates (e.g., 10 quanta/h per person), the purifier may not

remove particles as fast as they are emitted, resulting in a higher infection probability. This is illustrated in Figures 5b and 6b, which show infection risk within a day of exposure under different ventilation strategies.



) b)

Figure 5. Infection risk probability during the measuring period (a) and withing a day of exposure (b) in the COVID ward



a) b)

Figure 6. Infection risk probability during the measuring period (a) and withing a day of exposure (b) in the ICU room

When comparing ventilation strategies, the infection risk is highest with natural ventilation alone, as shown in Figures 5a and 6a. Mechanical ventilation with 12 ACH offers the best performance, significantly reducing infection risk due to the higher air exchange rates that dilute airborne pathogens. Conversely, mechanical ventilation with 4 ACH is less effective, especially when the quanta emission rate is higher, as it may not reduce pathogen concentration quickly enough.

In the COVID Ward (volume of 42.3 m^3), infection risk is higher due to the smaller volume, which limits the air dilution effect. Even with natural ventilation combined with an air purifier, infection risk remains relatively high at higher quanta emission rates. In contrast, the ICU room, with a larger volume of 80.6 m^3, demonstrates lower infection risk due to better dilution of airborne pathogens. This is evident in Figure 6b, where the larger volume and recirculation provided by the fan coil system help disperse particles more effectively.

The results highlight the impact of room volume, ventilation rates, and quanta emission rates on infection risk. Natural ventilation combined with air purification can reduce infection risk, but mechanical ventilation with higher ACH remains the

most effective method for ensuring low infection probabilities, particularly in smaller rooms or when quanta emission rates are high.

8.4.7 Discussion

This study has several limitations. While the dynamic simulations in IDA ICE provide valuable insights into airflow and ventilation strategies, the software does not model particle concentration directly, which may impact the precision of infection risk estimates. In addition, the study relies on general assumptions for quanta emission rates and window opening schedules, which may not fully reflect real-world variations in hospital operations. Future research could address these limitations by incorporating real-time patient data, more detailed airflow measurements, and testing the performance of air purifiers in diverse hospital environments.

8.4.8 Conclusion

This study assessed infection risks in naturally ventilated hospital rooms, focusing on a COVID Ward and an ICU room. The main conclusions are that natural ventilation alone is inadequate for controlling infection risks, especially at higher quanta emission rates. However, the addition of air purifiers significantly reduces infection risks when combined with natural ventilation, improving overall air quality. Room volume plays a critical role, with larger spaces like the ICU benefiting from better air dilution and lower infection risks. Mechanical ventilation remains the most effective method for infection control, particularly in smaller rooms or higher-risk scenarios. Ultimately, tailored ventilation strategies are necessary, with mechanical systems prioritized in high-risk environments, while air purifiers can supplement natural ventilation where mechanical retrofitting is not feasible.

8.4.9 References

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8.5 Influence of ventilation and filtration on $PM_{2.5}$ concentrations and infection risk probability in the indoor air of European Hospitals

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Abstract: Indoor air quality was evaluated in three hospitals across different European cities with varying ventilation systems. Findings show that air quality is affected by location, building design, and indoor activities. Air purifiers reduced particulate matter (PM) concentrations in all cases, including those with initially low particle levels like in Finland. The benefits of portable air purifiers are especially notable in highly polluted environments, such as Romania.

8.5.1 Introduction

The quality of the indoor air is affected by outdoor and indoor pollution sources. Outdoor air quality varies based on geographical location (Lepistö et al., 2023) and human activities. Although most air quality studies (AQ) focused on outdoor exposure, people spend most of their time indoors. The objective of this study was to understand the differences in the characteristics of some aspects of the indoor and outdoor metrics of ambient particle pollution, including airborne particulate matter ($PM_{2.5}$), black carbon (BC), and lung-deposited surface area (LDSA), in hospital buildings across different geographical regions and urban environments in Europe. By comparing indoor and outdoor (I/O) PM concentrations in three case studies, the study investigated the effectiveness of various ventilation and air purification technologies in reducing particle concentrations.

8.5.2 Method

Three hospital buildings were selected for this study, each located in different European cities: Bucharest in Romania, and Espoo and Helsinki in Finland. These cities represent diverse geographical locations with varying traffic volumes in nearby areas. The selected hospital buildings employ different types of ventilation and filtration technologies (Olsson, 2017). The case study in Bucharest involves a building constructed in the early 20th century. This building is entirely naturally ventilated, relying on openings such as doors and windows to provide fresh air. In this system, the outdoor air is driven by natural phenomena, with no control over

the quality of the air entering the building. The case study in Espoo represents a hospital with a traditional mechanical ventilation system. This building was constructed in 1976 and underwent renovations between 1995 and 2020. It utilizes a constant air volume (CAV) ventilation system. Lastly, the case study in Helsinki features a hospital equipped with a modern mechanical ventilation and filtration system, reflecting the most advanced technologies among the three case studies.

Three distinct measurement campaigns were conducted in each of the case study buildings. Each campaign lasted one week and involved the use of advanced, approved sensors, complemented by continuous measurements from other commercial sensors. These long-term monitoring campaigns provided insights into seasonal variations and trends in the collected data, while the intensive one-week campaigns offered detailed information on both indoor and outdoor characteristics specific to each case study. Although each case study was unique in its location, design and use, all monitoring campaigns adhered to a standardized measurement protocol to ensure consistency and comparability of the data for analysis. The campaigns assessed various indoor and outdoor parameters, including particulate matter ($PM_{2.5}$), lung-deposited surface area (LDSA), black carbon (BC) concentrations, CO_2 concentrations, as well as air temperature and relative humidity.

An intervention was carried out in two of the case study buildings: the naturally ventilated hospital in Bucharest and the hospital with a traditional mechanical ventilation system in Espoo, involving the use of portable air purifier units. The purpose of this intervention was to assess the effectiveness of these units in improving air quality and reducing infection risk by lowering particulate matter concentrations to the levels recommended by the World Health Organization (WHO) (WHO, n.d.). Additionally, an infection risk model was developed for each case study, estimating the probability of infection risk (Noakes & Sleigh, 2008) under the existing conditions and with interventions such as the use of portable air purifiers or adjustments to the mechanical ventilation system settings.

8.5.3 Results

In terms of geographical location and ventilation system, the impact of outdoor air quality was particularly evident in Bucharest, which relies entirely on natural ventilation. After implementing portable air purifiers in two patient rooms within the hospital building in Bucharest, the $PM_{2.5}$ concentrations decreased significantly, reaching a low of 1.0 µg/m³ in an isolation room. In the ICU room, the indoor $PM_{2.5}$ concentration remained below the recommended limit of 15 µg/m³ (see-Figure 1).

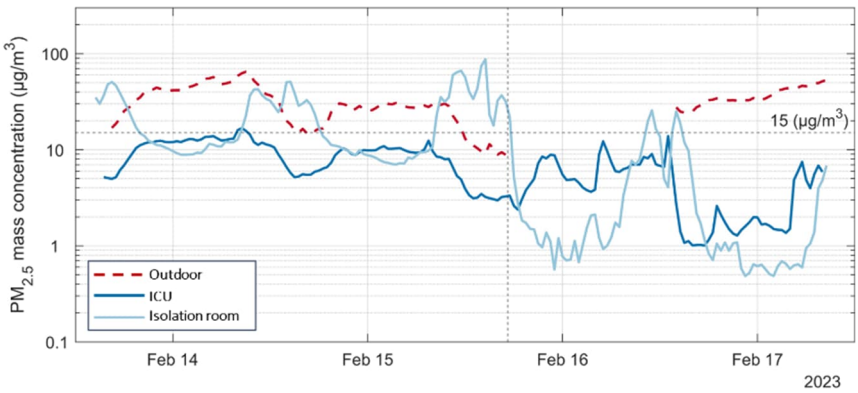

Figure 1 $PM_{2.5}$ mass concentration (time series) before and after installing the air purifier – Bucharest case

In Helsinki case (see-Figure 2), both outdoor and indoor air quality in terms of $PM_{2.5}$ concentrations were within the WHO guidelines (i.e., 24-hour average concentration of 15 µg/m^3) (WHO, 2021)

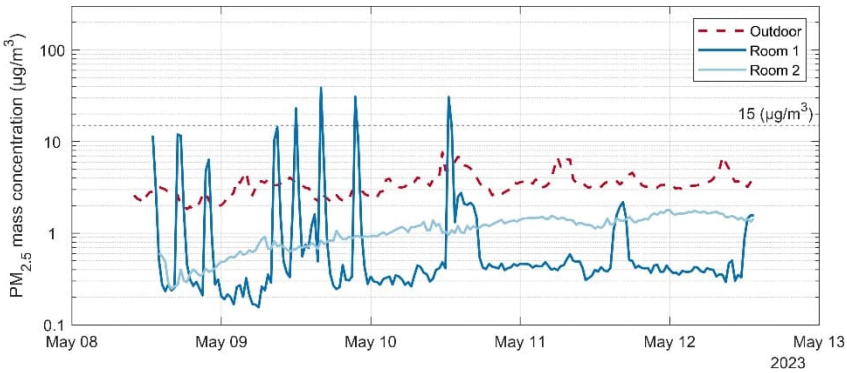

Figure 2 $PM_{2.5}$ mass concentration (time series) – Helsinki case

In the Espoo case (see-Figure 3), as in Helsinki, both outdoor and indoor particulate matter (PM) concentrations were below the WHO-recommended thresholds. However, indoor PM concentrations demonstrated a clear correlation with outdoor levels. To evaluate the effectiveness of the portable air purifiers in two patient rooms, the indoor-to-outdoor (I/O) $PM_{2.5}$ concentration ratio was calculated. Following the installation of the air purifiers, reductions in the median I/O ratio were observed, with a 58% decrease in room 4 and a 36% decrease in room 6.

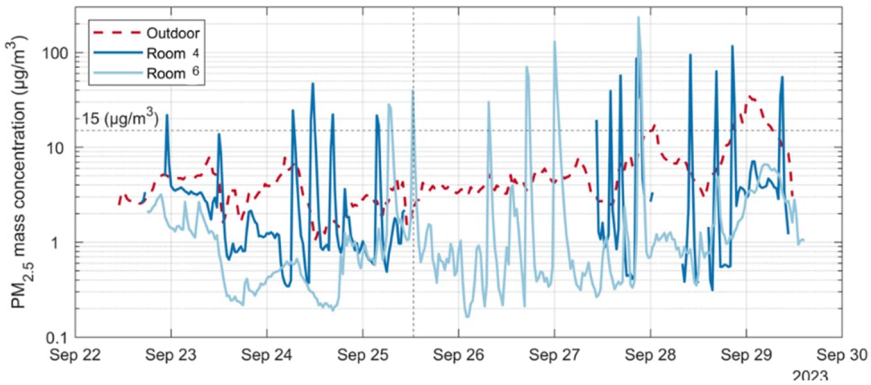

Figure 3 $PM_{2.5}$ mass concentration (time series) before and after installing the air purifier–Espoo case

Infection probabilities were calculated for all case studies. Figure 4 shows the increase in infection probability over time in the isolation room in Bucharest under three conditions: natural ventilation, the use of air purifiers, and varying infectious dose rates. In all scenarios, the probability of infection rises rapidly within the first few hours. However, the probability is halved with the implementation of air purifier units and is further reduced with the presence of a mechanical ventilation system.

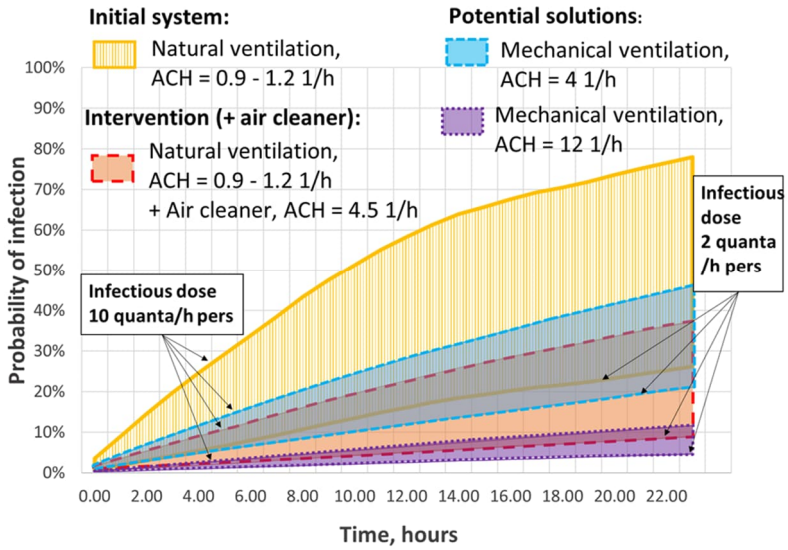

Figure 4 Infection risk probability within a day of exposure with and without air cleaners in Isolation room - Bucharest case

In the Helsinki case, the infection risk probability was the lowest even without any interventions, owing to the high air changes per hour (ACH) already in place at the hospital. However, if portable air purifiers were introduced or the ACH increased further, the infection risk probability could be reduced to as low as 10% and 5%, respectively (see-Figure 5).

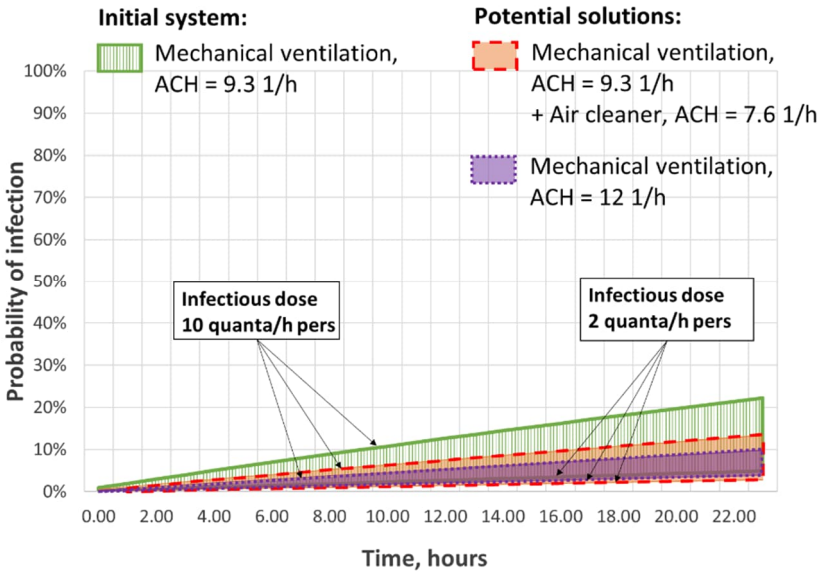

Figure 5 Infection risk probability within a day of exposure with and without air cleaners in Isolation room - Helsinki case

In the Espoo case, the infection risk probability was slightly higher compared to the Helsinki case, despite the presence of a mechanical ventilation system (see-Figure 6). This disparity was attributed to the measured ACH being lower than the designed value, indicating a performance gap. If this gap were addressed, the infection risk could potentially be reduced to as low as 40%. The integration of air purifiers or an increase in ACH to the values recommended by the R3 Nordic Guidelines for hospital ventilation (i.e., 12-24 ACH) (Solem et al., 2023), would significantly decrease the infection risk probability to 15% and 10%, respectively.

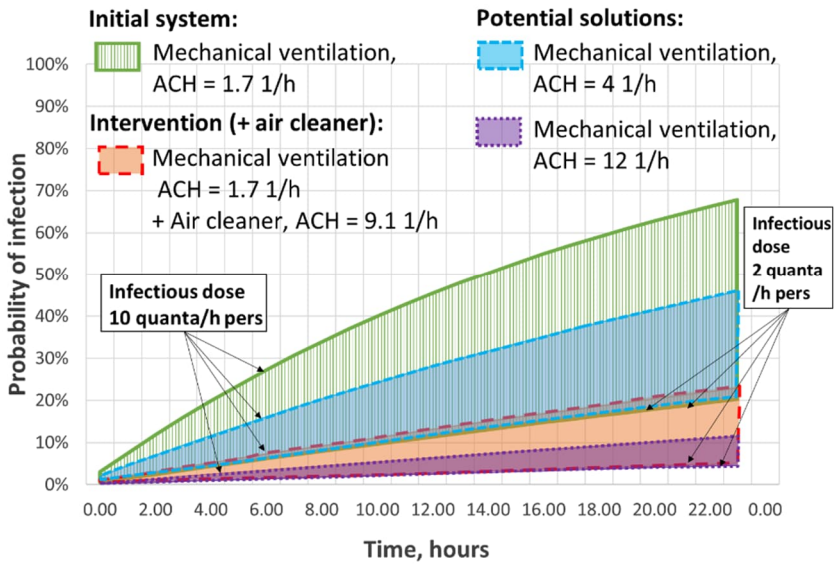

Figure 6 Infection risk probability within a day of exposure with and without air cleaners in Isolation room - Espoo case

8.5.4 Conclusions

Indoor air quality is influenced by geographical location, building characteristics, ventilation systems, and indoor activities. In the case studies investigated, the reduction in $PM_{2.5}$ mass concentration following the use of air purifiers highlights the potential benefits of employing portable air purifiers in hospital settings, even in environments with low particle concentrations, such as in Finland. This is critical for mitigating aerosol transmission and thereby reducing the risk of infection among hospitalized patients. The advantages of using portable air purifiers are particularly pronounced in highly polluted environments, such as in Romania. Additionally, portable air purifiers may facilitate the circulation of filtered air within the indoor space, which can further contribute to reducing infection risk in hospital buildings where airborne viruses pose significant risks to patients and staff.

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8.6 Numerical study with LES on how to exploit air purifiers in poorly ventilated corridor-like spaces

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Abstract: High-resolution Large-eddy Simulation (LES) is utilized to examine how air purifiers can be effectively employed in poorly ventilated indoor environments. Here, the focus is on corridor-like indoor geometries (like waiting lobbies in health care facilities) which are challenging environments in the context of indoor air hygiene. The study shows how air purifiers are able to operate at significantly better efficiency when fans are added to enhance the mixing and advection of the indoor flow system.

8.6.1 Introduction

This study utilizes high-resolution PALM LES modeling (see Chapters 4.3 and 4.4) to investigate how air purifiers can be efficiently utilized in corridor-like spaces with poor ventilation capacity. Corridor-like indoor spaces constitute a challenging geometry for air hygienic considerations because, in the absence of sufficiently sized mechanical ventilation system, they carry a natural tendency to form local peaks in pathogen concentration fields arising from local sources (like infected individuals). This study is motivated by E3 project's Use Case 1 which examines techniques to improve indoor air hygiene of existing health care facilities. Here the focus is on studying the evolution of pathogen concentration within corridor-like geometries hosting potentially large groups of people. Such circumstances occur frequently, for example, in various health care facilities. This study is comparative, placing priority in recognizing the differences arising from modified ventilation, filtration and mixing conditions. This investigation is a continuation of a previously published work on utilizing air purifiers in a complex indoor environment (Auvinen et al., 2022).

8.6.2 LES model setup for waiting lobby

The LES model in this study is constructed to closely resemble a real hospital waiting lobby geometry. However, the model has been augmented with additional features, such as a conventional ventilation system with a single inlet and an outlet at opposite ends of the corridor-like lobby. This was necessary to expand the applicability of the study and to achieve more generalizable conclusions. Figure 1 below illustrates the model geometry, lists the essential dimensions and highlights the locations for the ventilation system inlet and outlet, added air purifier (center) and simple mechanical fans (both ends of the corridor). The location of the pathogen source is altered in this study to ensure that the conclusions are not

specific to their application-specific placement. The locations were $X_{s1} = L/3$ (denoted L, 'left') and $X_{s2} = 2L/3$ (denoted R, 'right') and the source height is always 1.36 m.

The LES model has 2 cm spatial resolution which has been demonstrated via rigorous validation study (chapter 4.5) to yield sufficiently reliable predictions concerning pathogen dispersion outcomes indoors. The model includes 12 manikins whose skin temperature is 4 degrees higher than the ambient air, introducing a weak addition of momentum due to buoyancy into the flow system. Computational tests were carried out with different levels of skin temperature to confirm that this modelling choice had no meaningful effect on the results.

The air purifier in the model was constructed to closely mimic a commercially available device whose filtration capacity in this study is set at $Q_{flt}/V = 2.2$ in terms of air changes per hour. The purifier's suction inlet is at the bottom of the device whereas the filtered air is ejected upward with a small angle into the room (see Figure 1).

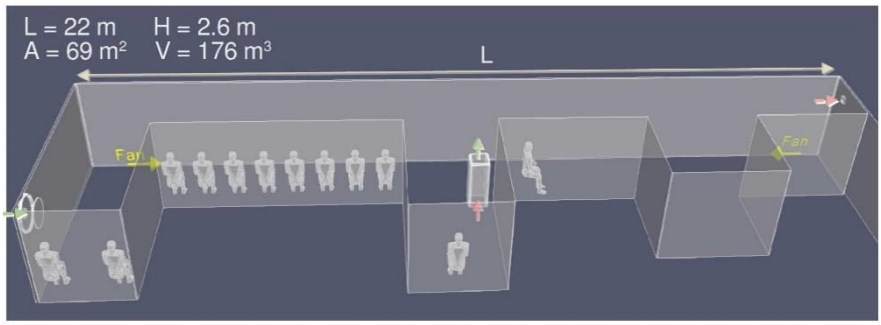

Figure 1: Visualization of 3d LES model geometry utilized in the study. The model includes 12 manikins, a centrally placed air purifier, ventilation system inlet and outlet, and two optional fans (modelled as local momentum sources) shown with yellow arrows to indicate their flow direction.

8.6.3 LES simulation results

Results from six simulations listed in Table 1 below are presented herein. Each simulation is run for 2 hours of simulation time, which is identified as the theoretical time scale for the evolution of pathogen concentration under chosen clean air delivery rates (CADR), and sufficiently long time to capture the relevant air hygienic performance of the considered indoor flow systems.

Table 1: Listing of six different simulation cases included in this study and their respective volume flow rates. The ventilation system flow rate is set at very low level to represent a poorly ventilated case. The labels adhere to the following shorthand: REF (L/R): reference case with poor ventilation and source location on left/right of the corridor, +A (L/R): addition of an air purifier to the system, +A+(2)F (L/R): further addition of one or two 10 Watt (net mechanical power) fans to augment the mixing and transport of the flow system.

Label:	**REF (L)**	**REF (R)**	**+A (L)**	**+A (R)**	**+A+F (L)**	**+A+2xF (R)**
$\frac{Q_{vent}}{V}$ (h^{-1})	0.1	0.1	0.1	0.1	0.1	0.1
$\frac{Q_{flt}}{V}$ (h^{-1})	0.0	0.0	2.2	2.2	2.2	2.2
Total (h^{-1})	0.1	0.1	2.3	2.3	2.3	2.3

In this study a scaled mean concentration is utilized as a global indicator for the air hygienic performance of the indoor flow system. The concentration field in each case is scaled identically to facilitate a meaningful and convenient comparison. Figure 2 presents these evolution curves, (a) depicting the REF and +A cases and (b) including the addition of simple fans to the system. The reference case with poor ventilation conditions exhibits, as expected, a nearly linear growth curve

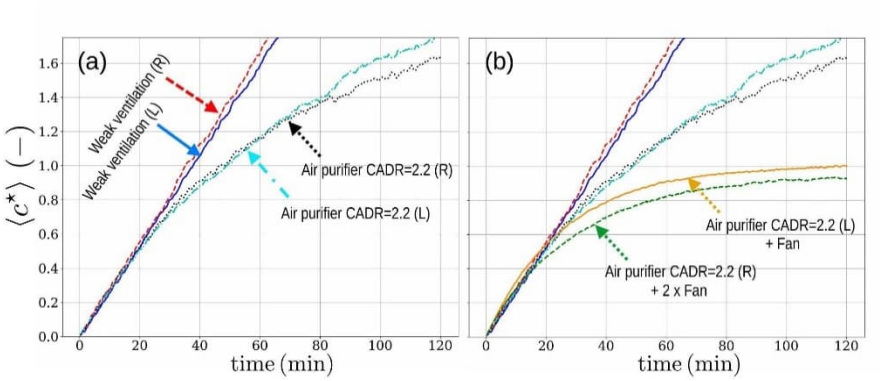

Figure 2: Evolution curves for scaled non-dimensional mean concentration within the corridor-like space under different ventilation and filtration conditions. The scale is chosen to simplify the comparative analysis. Figure 2(a) depict two reference cases with poor ventilation conditions at two different source locations (left, L and right, R) juxtaposed to otherwise identical cases but featuring an air purifier with clean air delivery rate (CADR) of 2.2 air changes per hour (ACH). Figure (b) adds two additional cases where simple fans have been added to the room to enhance the mixing within the room. The results highlight the importance of distributing the pathogen concentration throughout the room such that the air purifier can perform the cleaning at its nominal capacity.

which is altered by the addition of an air purifier. However, the addition of an air purifier does not bring about the best possible performance gain because, as shown in Figure 2(b) the introduction of augmented mixing and corridor lengthwise advection via fan(s) significantly improves the efficiency with which the air purifier reduces the overall concentration level.

The improvement in air purification efficiency due to enhanced mixing and crossflow in the room can be further demonstrated by visualizing vertically averaged concentration distribution $\langle c^* \rangle_z(x, y)$ as shown in Figure 3. Here, instantaneous snapshots from three cases (REF (L), +A (L) and +A+F (L) in Table 1) at t=90 min are shown, all having the source location on the left side of the corridor as indicated by red crosses. The local effect of the air purifier is immediately apparent in Figure 2(b) where the device acts as a barrier for the concentration field but leaving the near source area with a region of elevated

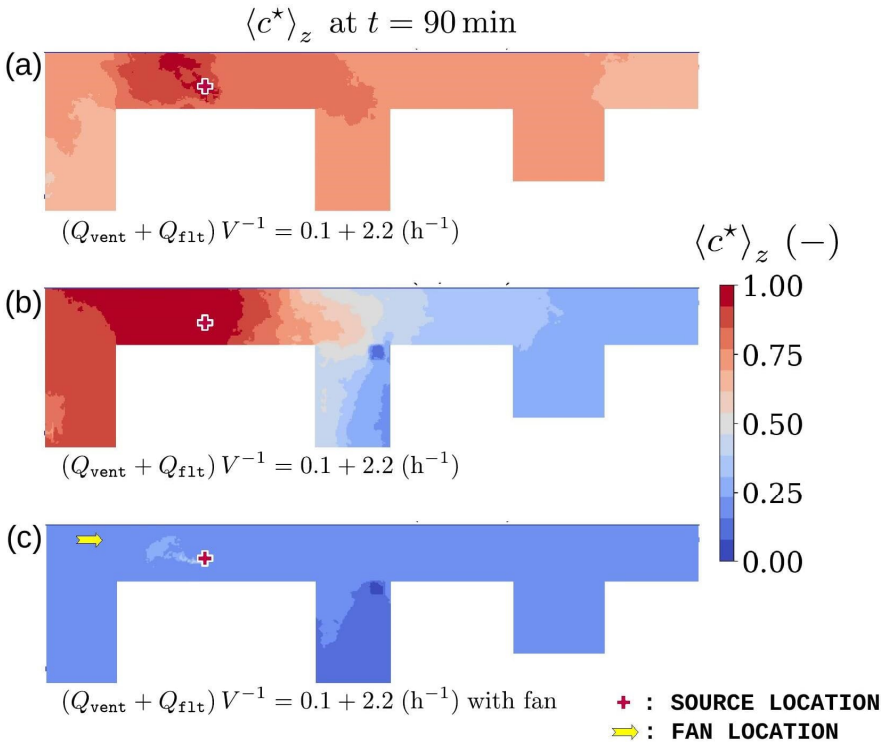

Figure 3: Comparative visualization of vertically averaged pathogen concentration fields within the room 90 minutes after the pathogen source has been active. The scale has been chosen to facilitate a meaningful comparison. The reference case without proper ventilation is shown in (a) whereas case (b) introduces an air purifier (CADR=2.2 volumes per hour) and (c) further augments the system with a fan supplying 10 Watts of net mechanical power. The source location is marked with a red plus -sign and the fan location with a yellow arrow.

concentration level. The addition of a fan, which provides both enhanced mixing and flushing crossflow across the corridor, is effectively able to dissolve and transport the near source concentration peak in a manner that allows the air purifier to act on it. The outcome is apparent in Figure 3(c) which exhibits a significantly improved overall outcome. A weak plume originating from the source towards the fan is visible in the figure which may appear counter intuitive. However, this behavior is explained by the fan being located near the floor causing recirculating flow to occur at the source location.

The contributing mechanisms relevant to this problem and also the interplay between an existing ventilation system and air purifiers in such indoor geometries will be further examined, quantified and documented in scientific journal publication (to be submitted).

8.6.4 Conclusion

This numerical study, exploiting high-resolution LES analysis, provides a distinct contribution to the understanding of how air purifiers should be employed optimally in corridor-like indoor environments. The pathogen dispersion simulations made evident that the air filtration capacity of air purifiers can be better utilized in poorly ventilated spaces when the indoor flow system is augmented with enhanced mixing and lengthwise advection.

8.6.5 References

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8.7 Concept plan of integration of hydrogen peroxide vapor decontamination into hospital building automation system

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Abstract: Peroxide vapor (HPV) has been shown to be effective against various pathogens, including drug-resistant strains (Ahmed and Mulder, 2021). Case studies involving HPV decontamination tests in patient rooms at HUS Helsinki University Hospital demonstrated a 2.5 to 3.6 logarithmic (log) reduction (99.68–99.97% reduction) in bacterial samples and a 6-log reduction in most of the biological indicators. These case studies, along with a literature review, formed the basis for the development of a conceptual plan of a building automation integration of an HPV decontamination system for Granlund Oy.

8.7.1 Introduction

Drug-resistant pathogens cause difficult-to-treat illnesses and in Europe alone, over 33,000 deaths are caused by infections that can no longer be treated with antibiotics (“Antibioottiresistenssi - THL,” 2023). Antimicrobial-resistant bacteria can spread in hospital environments and surfaces contaminated by resistant bacteria can cause infections for a long time, even after the patient has been transferred away (Otter et al., 2013).

Currently, hospital rooms and surfaces are cleaned by hand using disposable and non-disposable cloths with different cleaning and disinfection agents. Cleaning frequency and meticulousness depend on available resources, the criticality of the room, and the observed dirt. Operating rooms are cleaned several times a day, with a quick intermediate cleaning after every operation and a more thorough cleaning at the end of the day or if the operation has resulted in a lot of cleaning to be done.

Hydrogen peroxide is a versatile cleaning agent that is effective against multiple pathogens, including drug-resistant ones. Hydrogen peroxide vapor (HPV or VHP) is beneficial, as it can decontaminate all surfaces of an entire space, including those that are hard to reach with regular hand-cleaning.

HPV decontamination machines have been available for over ten years and have proven to reach high-quality cleanliness levels in optimal conditions. Current HPV room decontaminating systems require several manual steps to initiate an otherwise automated process and to ensure a safe and efficient outcome. Additionally, current HPV systems require monitoring to guarantee the safety of the decontamination process.

This project aimed to develop a conceptual plan for integrating of a hydrogen peroxide vapor room decontamination system into the building management system (BMS). By automating and integrating the HPV decontamination system

into the BMS system, the required manual steps can be reduced, safety increased, and human resources freed for other tasks. The integration plan was designed to fit an operation room because it has among the highest cleanliness requirements and is usually equipped with high-end automation and HVAC technology, making the integration process easier.

Another objective of this project was to explore the potential of an HPV room decontamination system for cleaning surfaces in hospital environments. The goal aimed to verify the quality of the decontamination process, determine the complete decontamination cycle time, assess the level of decontamination quality in spaces consisting of multiple rooms, and investigate methods to prevent hydrogen peroxide vapor leaks during decontamination of a room with no door sealing.

8.7.2 Research methods

The research methods in this project included a literature review, a consultation meeting with HUS hospital cleaning professionals, and case studies including HPV decontamination experiments.

The literature review aimed to gather essential information on hydrogen peroxide vapor decontamination. The review examined, among other things, the disinfecting properties of hydrogen peroxide, safety regulations related to hydrogen peroxide, hospital building ventilation systems, and building automation. The literature review also examined the hydrogen peroxide based automatic decontamination methods currently in use, especially hydrogen peroxide vapor decontamination. Scientific articles were the main source of the literature review.

A consultation meeting was held with the staff of HUS to discuss the cleaning methods of operating rooms and general practices related to cleaning and operating rooms. Hospital staff with experience and expertise in cleaning operating rooms, hospital hygiene, and infection control attended the meeting.

In the case study, VHP decontamination tests were conducted in various areas of Meilahti Hospital area which is part of HUS Helsinki University Hospital. The first part of the case study decontamination tests were conducted in Meilahti Bridge Hospital and the second part of the case study decontamination tests were conducted in Meilahti Triangle Hospital and in Meilahti Tower Hospital.

The decontamination tests were carried out in accordance with the requirements of standard SFS-EN 17272:2020. The quality of the decontamination was verified with dried live bacteria (Staphylococcus warneri and Bacillus atrophaeus) mixed with Bovine serum albumin (BSA, 0,3g/l), biological indicators (Apex® EZTest®) and with indicator tape.

Hydrogen peroxide vapor for decontamination tests was generated with a prototype hydrogen peroxide vaporization machine (Halton Vita VCS-750) produced by Halton Oy and Cleamix Oy. VCS-750 was also utilized to remove the excess hydrogen peroxide vapor after the decontamination process with its Hydrogen peroxide vapor concentration, temperature, relative humidity, and relative saturation were measured from the decontaminated room air with four or five Vaisala PEROXCAP HPP272 sensor probes. HPP272 probes were integrated

into the Halton Vita VCS-750, and they were used to adjust the desired hydrogen peroxide vapor concentration.

8.7.3 Results and findings

The first part of the case study was conducted in operating room 29 located in Meilahti Bridge Hospital. Five decontamination tests with four complete decontamination cycles were conducted in the operating room with different settings and situations. The main goals of these decontamination tests were to verify the quality of the decontamination process and the complete decontamination cycle time with different decontamination settings.

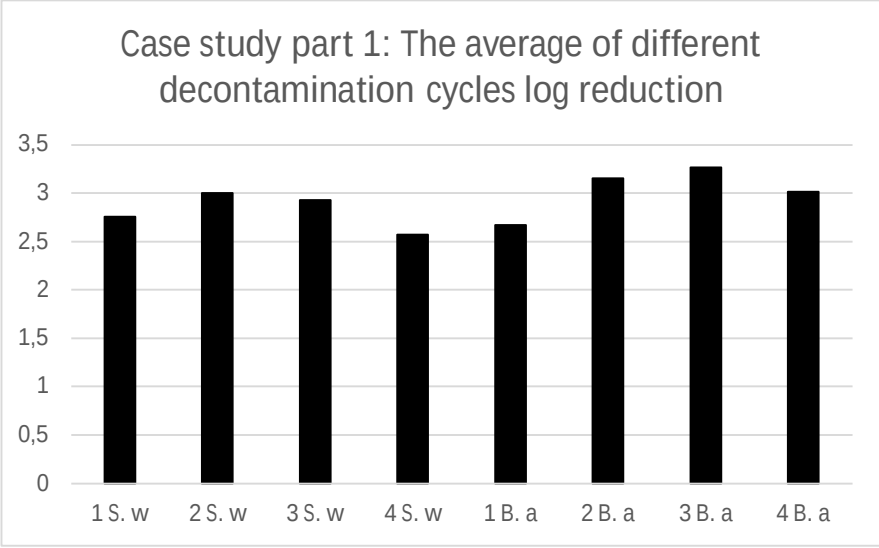

Figure 33. The averages of S. warneri and B. atrophaeus logarithmic reductions in four different decontamination cycles (tests 1-5).

The second part of the case study was conducted in Ebola room and in another isolation room located in Meilahti Triangle Hospital and in a conventional patient room located in Meilahti Tower Hospital. Three different decontamination tests were conducted in these three rooms.

The second part of case studies aimed to verify the results of decontamination and the total time of the process. In contrast to the first part of the case study, the decontamination experiments also aimed to determine the level of decontamination in different parts of the apartment when decontamination was carried out using a hydrogen peroxide vapor generator placed in one room. The decontamination tests also investigated how the hydrogen peroxide vapor leakage into the corridor during decontamination could be prevented by depressurizing the

area. The effect of depressurization was studied in a conventional patient room where the door gap was not sealed as in isolation rooms.

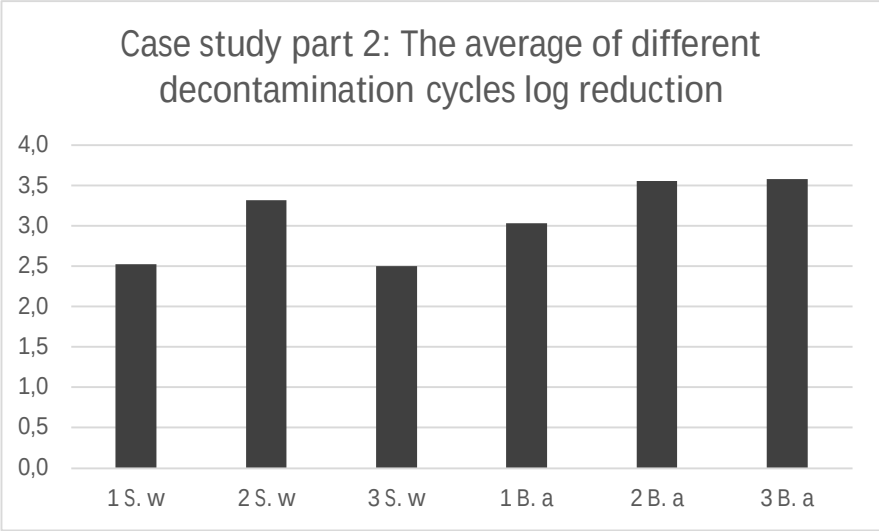

Figure 34. The averages of S. warneri and B. atrophaeus logarithmic reductions in three different decontamination cycles. Room coding: 1 Ebola room, 2 isolation room and 3 conventional patient room

Table 13. Table of results from the decontamination tests made in Case studies including average log reduction values, complete cycle times and ramp down times for each decontamination cycle.

	Decontamination cycle	Average log reduction	Average log reduction B.atrophaeus	Average log reduction S.warneri	Complete cycle time (min)	Ramp down time (min)
Case study part 1	1	2,71	2,67	2,76	215	95
	2	3,08	3,15	3,00	230	48
	3	3,10	3,27	2,93	440	84
	4	2,79	3,01	2,57	252	70
Case study part 2	5	2,78	3,03	2,52	425	115
	6	3,44	3,56	3,32	345	85
	7	3,04	3,58	2,50	310	60

The decontamination tests provided the basis for developing a conceptual plan to integrate a decontamination system with a building management system (BMS). The plan was further informed by case studies, literature reviews, and input from HVAC and hospital cleaning professionals.

The conceptual plan had three primary objectives: to reduce the amount of manual work required for the hydrogen peroxide vapor decontamination process by implementing automation methods, to improve system safety through automation, and to serve as a support material for the decontamination system's BMS design. In addition, the plan had two secondary objectives: to use the conceptual plan as teaching material and to propose a BMS design for the decontamination system.

8.7.4 Conclusions

The decontamination tests confirmed the spread of hydrogen peroxide vapor to all decontaminated rooms. The removal of hydrogen peroxide vapor was also carried out effectively and in a reasonable amount of time without hydrogen peroxide vapor leaks in most of the decontamination tests.

The average duration of all decontamination cycles conducted in case studies was 5 hours and 16 minutes. In the decontamination cycles, aeration (removal of hydrogen peroxide vapor) was achieved in the best case in about 50 minutes, and on average, aeration was achieved through the combined effect of ventilation and catalysis in about 80 minutes. The hydrogen peroxide vapor concentration during decontamination, the size of the space being decontaminated, and the efficiency of ventilation had the most significant impact on the ventilation time.

The targeted hydrogen peroxide concentrations were not achieved in every decontamination test. Especially achieving high levels of hydrogen peroxide vapor concentrations caused difficulties in bigger test spaces. In the case of the second study, in large multi-part rooms such as the Ebola ward, even hydrogen peroxide vapor concentrations were not achieved uniformly due to the complexity and extent of the room.

Based on the results of the decontamination tests, the test-specific average log reductions of S. warneri and B. atropheus bacteria treated with albumin solution (BSA) ranged from 2.5 to 3.6 log units (99.68-99.97% reductions). The average reduction of all bacteria in all tests was 3.0 log units. The log reductions in the bacterial samples were less than 6 log units, which was the target value in some tests. Standard SFS-EN 17272:2020 requires 4 to 5 log reduction depending on the test microorganism on medical area. However, in many other applications, a 3 log unit reduction (99,9% reduction) in microbes on surfaces can be considered a good decontamination result. A 6 log reduction (99.9999%) was achieved with all biological indicators, except for two indicators located in a distant corner of the Ebola Room during decontamination cycle 5 in the second part of the case study.

The conceptual plan included solutions to reduce the amount of manual work associated with different stages of the decontamination process by automating building technology functions related to preparation and post-processing, as well

as monitoring the decontamination process. The plan also included solutions to improve process safety and automate safety measures. The conceptual plan is a comprehensive document that describes the hydrogen peroxide vapor decontamination process, the integrated decontamination system, and its functions from the perspective of a building management system designer. The conceptual plan supports the BMS designer in the integration of the decontamination system and allows the BMS designer to participate in the decontamination system integration project without prior knowledge of hydrogen peroxide vapor decontamination methods.

The solutions and operating models developed in the conceptual plan should be verified through practical tests before being incorporated into the actual decontamination system design and implementation. Especially the functions essential for the safety of the decontamination system should be tested in an operating room environment or a similar space using a hydrogen peroxide vapor system or a simulated system.

8.7.5 References

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8.8 Experiments in reducing surface microbial levels within Hospital Environments and cleanrooms using new Hydrogen peroxide vapour technology

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EXTENDED ABSTRACT

8.8.1 Background

Healthcare associated infections are a challenge that causes hundreds of thousands of infections for both patients and healthcare workers in hospitals annually in every country. This challenge is expected to be growing concern due to emerging number of multi-resistant microbes in hospital environments. In addition to biosafety cleanrooms areas of especial concern are the ones, where patients are treated such as isolation rooms, patient rooms, treatment rooms and operating rooms.

Daily cleaning is the primary activity in reducing microbial debris from hospital environments. Although regular cleaning maintains environments clean it is not alone sufficient to remove microbial risk totally. A supplementary disinfection/decontamination means would provide additional safety towards microbes. In this research focus was to study application of vaporized hydrogen peroxide for 3-6 log reduction of microbes to be applied for regular maintenance of microbes in hospital environments.

8.8.2 Methods

Vaporized hydrogen peroxide (VHP) is a very effective disinfectant for large variety of microbes and it is widely used in different environments requiring high microbial hygiene. It could also be used moe widely in hospitals except as post cleaning decontamination also to periodic throughout reduction of microbe levels as well as for initial decontamination of premises prior cleaning – thus. Providing safety for cleaning personnel as well.

Some of the reasons why vaporized hydrogen peroxide is not used more widely in hospital environments relate to conception of the method being complicated and time consuming. A new method and device for more efficient and faster decontamination cycle and it's piloting in different hospital environments including operating room, isolation room and patient room is verified.

8.8.3 Results

The experimental validation proved that the new methos is applicable for enhanced microbial control also in hospitals and it may be applied safely for room decontamination.

8.8.4 Discussion and conclusions

Gaseous decontamination has been traditionally considered too complicated and time-consuming method for hospital environments. The verification of new device demonstrate that it was possible deliver uncomplicated process with consistent decontamination performance and shortened decontamination cycle.

8.8.5 References

Hagström K, Grönvall I, Björn S, Pennström L, Experiments in reducing surface microbial levels within Hospital Environments using Hydrogen peroxide vapour. *R3 Symposium 2023*.

8.9 Reducing Healthcare worker and patient to patient airborne exposure in patient and isolation rooms

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EXTENDED ABSTRACT

8.9.1 Background

Recent Covid pandemic has raised the public understanding on how important role airborne transmission plays in transmission of infectious microbes. Transmission in hospital patient rooms may take place both in patient healthcare worker (HCW) interaction, but also between patients sharing the same room.

Previous research have shown that with mixing ventilation that is the most common practise HCW exposure to patient outbreath may be five to ten fold in close proximity with patient compared to room average conditions.

On the other hand, even if single patient rooms have become much more common in new hospitals there still are many with multiple patient bedrooms as well. The Covid pandemic has also raised a new need for multi-patient rooms with isolation need to environment, when several Covid patients were treated in common intensive care rooms. An especial exposure situation would be in multi-patient ward, when medical treatment is provided to one of the patients, while others present in the same room.

8.9.2 Methods

A protective flow concept with dynamic airflow control, individual thermal environment and protective task airflow pattern has been developed to minimize both HCW and patient exposure risk.

The basic principle of the designed protective airflow system is presented in Figure 1. It is based on the use of parallel air streams supplying air towards patient bed that are created by two adjustable supply air diffusers located on both sides of the patient bed. The concept is completed by optimized positioning of the exhaust outlets.

During the development phase the airflow and temperature parameters have been optimized to provide both optimal protection and comfort conditions.

The same system principle has been applied for both normal ward and isolation room resulting in two variants of the system based on the different boundary conditions.

The patient ward system is based on two inward jets that are integrated with a radiant panel to provide necessary cooling and personal comfort control, like presented in Figure 1. The dynamic airflow is applied to be able to provide sustainable operation for patient only situations and active protective mode for patient treatment with HCW present.

Figure 35 Protective airflow system concept, patient room

The isolation room system has slightly different airflow principle; due to high airflow additional airflow patterns are directed towards sidewalls as shown in Figure 2. The isolation room system has also dynamic operation principle to allow sustainable operation, when room is used for normal patients and activating enhanced protective mode for either isolation or treatment situations.

Efficiency of the concept in reducing exposure risks of both HCWs and patients has been verified in the previous stages of research by full scale laboratory experiments for both patient and isolation rooms. The thermal acceptance of this task ventilation approach has also been studied using human subjects experiments.

Figure 36 Protective airflow system concept, isolation room

8.9.3 Results

Based on verification it is possible to reduce HCW exposure risk close to patient by 3 to 10 times with protective flow concept compared to current practise of mixing ventilation.

When applied in multi-patient wards patient to patient exposure risk may be reduced down to one 1/3 in patient rooms and one to 1/8 in isolation wards.

8.9.4 Discussion and conclusions

Current practices of air diffusion by mixed flow are not sufficient to protect HCWs nor patients in patient wards. Protective flow concept propose a task ventilation alternative, much more efficient approach to be applied for peoples safety in patient environments.

8.9.5 References

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Hagström K, Grönvall I, Kalliomäki P, Maula H, Sivula A, Reducing patient to patient airborne exposure in patient and isolation rooms with 2 patients. *Proceedings of Roomvent 2024.*

9 Daycare intervention

9.1 Introduction to the Daycare Intervention

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Abstract: Chapter 'Daycare intervention' provides an overview of the daycare study implemented as part of the E3 project in four daycare centers in Helsinki area. The purpose of the study was to examine the potential of air cleaning in reducing infections.

9.1.1 Introduction

Respiratory and enteric infections are common among children attending early childhood education, with many episodes occurring in a single winter. (Collins *et al.* 2018) These infections cause discomfort and distress to the infected children, increase healthcare expenses and can lead to outbreaks that affect not only the children attending the daycare center but also their families and the wider community.

The current paradigm of hygiene has been concentrating on prevention of spread by droplets and direct contact. COVID-19 began a change in the paradigm and recently many studies regarding increased air ventilation and air cleaning have been conducted. Previous research has shown that air cleaners can be effective in reducing concentration of airborne particles and bioaerosol in various settings, including hospitals, schools, and daycare centers. (Conway 2022, Falkenberg 2023, Alvarenga 2023)

However, clinical trials with clinical endpoints on effectiveness of interventions targeting only airborne pathogens have not been conducted. The aim of this work was to assess the relative importance of airborne transmission route in relation to fomite and contact infections. Day cares are infection rich environment where

contact transmission is almost impossible to mitigate. The intervention was conducted using portable air cleaners after careful evaluation of current ventilation system and infection risk modelling.

The study showed significant decrease in incident infections among the children during the intervention period and statistically non-significant decrease in parents work absences. The results support the importance of airborne particles as a significant transmission route.

9.1.2 Overview on papers in the chapter

The first research paper of the chapter by Vartiainen et al. outline the risk model used aid the placement and dimensioning of the air cleaners and provide experimental data to support the usefulness of the model. The effect of the intervention is reported separately.

The other paper of the chapter is by Ehder-Gahm et al. and provides insights on how to introduce sufficient clean air using appropriately sized air cleaners and ensuring these devices are optimally positioned within the premises.

Indoor air quality at four day care centers in Helsinki are covered in the paper by Silvonen et al. They employed a variety of sensors measuring airborne particulate matter and environmental parameters, and with research-grade measurement instruments measuring particle lung-deposited surface area and particle number concentration. The effect of using portable air purifiers was evaluated with respect to particle concentrations indoors.

Next paper by Täubel et al. gives information about the measurement of viruses from settled dust samples in the daycare study. They analyzed SARS-CoV-2, Influenza A/B, and Norovirus GI/GII using qPCR.

In the last paper of the chapter by Timonen et al. are described the measurements of indoor and outdoor air quality and their relations.

9.1.3 References

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9.2 The effect of room air cleaners on infection control in day care centres

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EXTENDED ABSTRACT

9.2.1 Background

Respiratory and enteric infections are frequent among children in early childhood education, particularly during winter, causing discomfort, distress, and increased healthcare costs. These infections can lead to outbreaks affecting families and communities, increasing parental absenteeism and stress. Enhanced ventilation and air cleaning, following the shift from droplet to aerosol transmission paradigms post-COVID-19, show promise in reducing airborne infection spread, though the exact relationship remains unclear.

Historically infection mitigation has focused on droplet and contact spread prevention. Air cleaners effectively reduce airborne particle concentrations in various settings, potentially lowering respiratory infection transmission risks. Effective air cleaner usage requires matching clean air delivery rates (CADR) to room sizes and existing ventilation rates. Various guidelines suggest CADR values relative to room area or ventilation rates to achieve desired air change rates (ACH).

The study aims to evaluate portable air cleaners' effectiveness in reducing respiratory infection risks in two daycare centers using a robust model. It estimates infection risks based on viral shedding rates and disease prevalence, offering insights into optimal air cleaner placement and infection hotspot identification.

9.2.2 Methods

The study was conducted in four day care centers in Helsinki, Finland. Day care centers were randomized into two sequences: day cares A and B in an Intervention-Control sequence, and day cares C and D in a Control-Intervention sequence. Children expected to attend throughout the study period were invited to participate during October 2022, with no exclusion criteria applied. 51 children were included in the final analysis. The study selected relatively new buildings in compliance with current building code requirements, equipped with modern mechanical ventilation systems featuring heat recovery and no recirculation of air. Incident infections were collected from the legal guardians by weekly electronic questionnaires.

To evaluate the impact of ventilation and air cleaning systems, a mathematical model was developed. The model estimates pathogen emission rates based on viral concentrations in respiratory fluids and the mass emission rate of droplets, which quickly dry and become airborne aerosols due to indoor conditions. Indoor air is assumed well-mixed in moderately sized rooms with adequate air change rates. The steady-state concentration of viral RNA copies per cubic meter depends on ventilation exchange rate, pathogen inactivation, deposition, room volume, and the air flow rate of air cleaners. The number of potential infectors is assumed proportional to disease prevalence and room occupancy.

The pathogen emission rate is influenced by activity and viral load in respiratory fluids. Inhalation and lung deposition of pathogen-laden aerosols are estimated using concentration, breathing rate, and exposure time, incorporating an alveolar deposition factor. Infection risk is calculated using the Wells-Riley equation, where D50 represents the infectious dose. The expected number of at-risk individuals is computed for each room in daycare centers where air cleaners were installed. The study was approved by ethical committee of Helsinki and Uusimaa (HUS/14231/2022) and was conducted according to Declaration of Helsinki.

9.2.3 Results

Modeling indicated that adding air cleaners could significantly reduce respiratory infections among daycare children. Risk varied widely across rooms based on occupancy and activity, with high-risk spaces having transmission probabilities over an order of magnitude higher than low-risk ones.

In a regression analysis, higher parental education was associated with reduced sickness absences, while child age and sex showed no significant associations. There were no significant differences between groups in parental education or employment type. Overall, the study period saw a nearly 20% reduction in incident infections.

9.2.4 Discussion and conclusions

In this work we showed that intervention targeted only to airborne transmission showed significant effect both in modelling and real-life. As we did not implement any other infection mitigation measures and children only spent part of their time in day cares airborne transmission is an important transmission route and air cleaners an effective way to mitigate risk of infections.

9.3 Dimensioning of air cleaners in day care centers including ventilation systems

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Abstract: A study on how to dimension air cleaners in daycare centers was conducted to minimize infection risk. Effective infection control requires sufficient clean air output relative to pathogen emission and ventilation. There are guidelines for dimensioning air cleaners, but they may not be suitable for different layouts, ventilation, user numbers, and usage patterns. Based on risk assessment, the air cleaners were placed and dimensioned so that the clean air flow rate in the premises more than doubled on average.

9.3.1 Introduction

In the past couple of years, we have all witnessed how quickly and effectively airborne diseases can spread from person to person. In addition to personal, sometimes long-term and severe symptoms, the widespread transmission of diseases imposes extra costs on our society, such as overburdening the healthcare system and disrupting various businesses. One critical environment for the spread of diseases is daycare centers, where a relatively large number of children and caregivers spend long periods together in confined spaces. Even if the building's ventilation system functions as designed, it may not always be sufficient to prevent the emergence of infection chains in daycare settings.

To address this, the E3 Pandemic Response Project consortium investigated whether air cleaning could reduce infections in daycare centers. The study aimed to reduce the spread of airborne diseases and design the efficient air purification system for selected daycare buildings. By sufficiently reducing the total pathogen dose, or overall exposure, the probability of illness should decrease. The goal was to use risk assessment to calculate the effective air cleaning setup for selected daycare centers, which also served as an intervention in four daycare centers in Helsinki.

There are several alternative approaches to sizing air cleaners. The choice of the most suitable method depends on disease-specific parameters, such as the average pathogen dose required for infection. Unfortunately, not all this information is always known, especially in advance, making the sizing process more challenging. On the other hand, certain principles, such as increasing the production of clean air, are applicable to reducing the concentration of any pathogen.

9.3.2 Considerations for dimensioning air cleaners

There are tools available for dimensioning air cleaners for individual premises (Table 1), such as the guidelines provided by REHVA (REHVA, 2021). Although useful in estimating the required air flow of the air cleaner, in most cases they do not consider the number of occupants in the space and their activity level which are the most dominant factors in sizing.

Table 1. Dimensioning guidelines for individual spaces.

Organization	**Criteria for room air cleaners**
REHVA (The Federation of European Heating, Ventilation and Air Conditioning Associations)	CADR (measured for particle size of 0.3 - 0.5 µm) should be 2 times greater than the outdoor air flow by the ventilation system in rooms with a ventilation rate more than 1 h^{-1}. If the ventilation rate is lower than 1 h^{-1}, the CADR should be at least 2 h^{-1}.
The Swedish Asthma and Allergy Association	CADR value is recommended to be 4 times the ventilation rate.
AHAM (The Association of Home Appliance Manufacturers)	Recommends the 2/3 rule, meaning the CADR of the air purifier should be at least two-thirds of the room's area corresponding to an air change rate of 5 h^{-1} in a room of standard height.
CDC (Centers for Disease Control and Prevention)	Recommend an air exchange rate of 5 h^{-1}.
ASHRAE (The American Society of Heating, Refrigerating and Air-Conditioning Engineers)	Provide a calculation method to determine the minimum equivalent clean airflow (l/s) required for different spaces to reduce the risk of airborne infection (ASHRAE Standard 241-2023: Control of Infectious Aerosols). Recommendation for example to educational facilities is 20-25 l/s/person multiplied by number of people in the breathing zone.

However, the situation often becomes more complex if you want to consider not only the different spaces and their ventilation solutions but also the usage profile of the spaces, the number of people present, and the quality of activities affecting particle emissions and the amount of inhaled air by exposed individuals to minimize infection risk (Figure 1). Over a long monitoring period, the disease situation and thus the likelihood of the presence of a person or persons spreading pathogens into the air also varies.

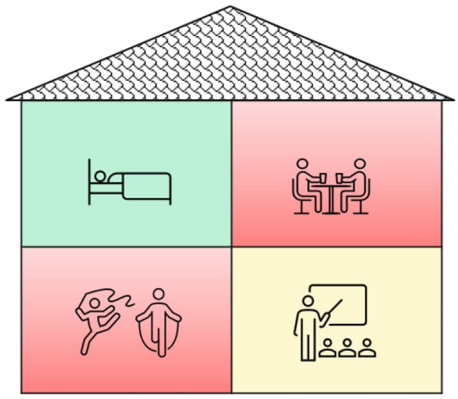

Figure 1. The different ways of using the building's premises affect the risk of exposure to airborne pathogens.

Optimal placement of air cleaners in different areas of a building requires a comprehensive assessment to achieve the best possible outcome with a limited number of air cleaners. The cumulative pathogen dose in the building's spaces must be reduced sufficiently to lower the probability of illness. However, not all initial data is always available accurately and reliably, so often relative improvements compared to the initial situation must be relied upon. Previous studies (Lewis, D. 2021) on super-spreader events reported globally can also be utilized to assess how significant changes in air quality are needed to achieve measurable health effects.

The Clean Air Delivery Rate (CADR) produced by air cleaners is a key criterion in their sizing. It must be matched to the room's ventilation to achieve sufficient reduction in concentration levels. However, lowering the concentration level requires relatively more clean air and thus more air cleaners. Therefore, it should be considered whether an additional air cleaner would be more beneficial in another area to reduce the overall infection risk in the building.

The operation of portable room air cleaners can be based on various techniques. To ensure that the air cleaners being implemented work as desired, the CADR produced by the cleaners must be reliably determined in advance. The CADR is determined using a standardized decay method, which examines the effect of the air cleaner on the concentration of a test substance (particles, gases, or microbes) in a test chamber. The CADR is obtained from the product of the test chamber volume and the rate of concentration decay, minus the decay caused by the test chamber itself. The study of CADR with particles takes into account the device's ability to filter fine particles, i.e., its efficiency, so the sizing of the air cleaner can rely solely on the amount of clean air produced. (IEC 63086-1, 2020)

The impact of the number of people present in a space on the risk of infection is quite clear, in addition to reducing the amount of pathogens in the air. The number of people affects the risk in two ways: it increases both the likelihood of having an infected person present as a source of pathogens and the number of potential

individuals exposed to airborne pathogens. Additionally, the probability of transmission in close proximity increases as the average distance between people decreases.

Also, the ventilation solutions of the premises have a significant impact on the level of infection risk. We often start from the assumption of complete mixing, which naturally never describes the situation in detail. The air cleaners should be installed in such a way that the air flow they cause does not disturb the general ventilation solution of the space too much. It is also possible to aim to direct the air produced by the air cleaners to the assumed breathing zone, in which case the cleaning effect is better than average. The effect is also improved by placing the air cleaner's intake close to the emission source or otherwise contaminated area.

9.3.3 Methods

The calculated dimensioning of daycare centers was done on the basis of **a risk assessment** in order to reduce pathogen concentrations to less than half of the original level (Vartiainen, V.A., 2024). The concentration calculation was stationary and based on the complete mixing model.

In the study, the design values of **the ventilation air flow rates** planned for the spaces were used as the starting values for the sizing. The realization of the design values was verified by measurements. The accuracy of the air volume realization is generally about ± 20% compared to the design values (Björkroth, M., 2019).

In the study, the utilization rate of daycare center spaces was surveyed using **a questionnaire on usage profiles.** Users of the spaces were asked to record the time spent and the number of people present in each space over the course of one day, with accuracy to the nearest hour.

The questionnaire also investigated the type of activities in daycare centers, classifying them into three categories: light activities (such as crafts), heavy activities (like singing and exercise), and sleeping. The quality of activities taking place in the spaces affects the number of pathogens released into the air. Light and calm activities produce fewer pathogens in the air compared to heavier, more vigorous activities. Additionally, the amount of air inhaled by exposed individuals varies according to their level of activity.

The air change rate (air changes per hour, **ACH**) indicates how many times per hour the air in a space is exchanged, and it is also sometimes a basis for sizing air cleaners. The air change rate of a space can be quite high due to ventilation alone. In such cases, the ventilation may be sufficient and adding a room air cleaner is not necessary.

9.3.4 Results

The study aimed to design **a dimensioning plan for air cleaners** to reduce the total exposure in the entire building to half of the original level. This goal was set

considering practical limitations and constraints, such as good ventilation in the spaces. The design was based on the guidelines provided by REHVA regarding the relationship between ventilation values and the clean air delivery rate of air cleaners. The design also considered the usage profile of the spaces, including the number of occupants and the nature of activities conducted in the spaces. Additionally, the ventilation rate resulting from the design was examined.

The exposure in different rooms was assessed by area, like the hallway, hall, small room, dining area, and group rooms. By using weighting factors based on usage profiles, the air cleaners could be strategically placed in the rooms to reduce exposure optimally and energy-efficiently throughout the building during the day, taking into account ventilation, occupancy rate, and activity levels.

The area of the different rooms in the daycare center was relatively small, less than 70 m². The realization of the designed ventilation values in the rooms was verified by measurements and the deviation from the planned values was about ± 18%. The ventilation in the rooms was mixing, and the air exchange rate was high (around 3-6 exchanges per hour), so it can be assumed that the impurities in the air were relatively evenly distributed.

Figure 2. Based on the risk assessment, daytime exposure in the studied kindergartens occurs mainly in group rooms, hallways, and dining rooms.

Based on **the risk assessment**, the exposure during the day in the daycare centers included in the study takes place especially in group rooms, hallways and dining rooms (Figure 2). To mitigate exposure in high-risk areas identified in the risk assessment, 45 air cleaners were installed across two daycare centers, bringing air quality in these areas to levels comparable to those in lower-risk

zones. The clean air output of the air cleaners was tailored to meet the specific sizing of each space. The study used air cleaners whose clean air delivery rate (CADR) was tested using particulate pollutants. The exposure throughout the daycare center was reduced to half of its initial level during the day.

The impact of air cleaners on the air change rate was also considered during the dimensioning. In some premises, the increase in the air change rate would have been very significant in the dimensioning according to REHVA's instructions, but with the dimensioning carried out based on the risk assessment, this could be taken into account. Based on **the risk assessment**, the exposure during the day in the daycare centers included in the study takes place especially in group rooms, hallways and dining rooms (Figure 2). To mitigate exposure in high-risk areas identified in the risk assessment, 45 air cleaners were installed across two daycare centers, bringing air quality in these areas to levels comparable to those in lower-risk zones. The clean air output of the air cleaners was tailored to meet the specific sizing of each space. The study used air cleaners whose clean air delivery rate (CADR) was tested using particulate pollutants. The exposure throughout the daycare center was reduced to half of its initial level during the day.

The successful **implementation of the dimensioning** relies on the usability of the devices and maintaining the desired clean air delivery rate. The air cleaners' clean air output should align with the calculated values across different usage scenarios. Therefore, to ensure the success of the health study intervention, **the controlled operation** of the devices was managed using remotely operated and readable smart plugs to ensure the desired performance level.

The placement of the air cleaners in the daycare centers took the general ventilation system into account. The air cleaners were positioned to avoid being near the supply or exhaust air outlets of the ventilation system. Additionally, the placement in each room was influenced by the furniture and functionality of the space. The air cleaners were installed to ensure an unobstructed outflow direction while preventing short-circuit flows between the outlet and inlet sides.

Due to the limited space in the daycare centers, we had to compromise somewhat on the clean air output in a few spaces. In small rooms, the devices can cause a feeling of draft in the close range of the air cleaner, and the noise produced by the devices can be disruptive, leading to the air cleaners being operated at a lower speed than designed. The lack of space also caused challenges for placing and bringing cleaners to the premises. Despite the challenges, the total exposure in the study was reduced to less than half of the original exposure.

Defining the desired reduction in concentration levels through intervention is complicated by the lack or difficult availability of essential initial data regarding the spread of infections. Due to incomplete or missing initial data, relative concentration targets compared to the initial situation were determined for different spaces.

9.3.5 Conclusions

The purpose of air cleaning is to dilute the concentration of airborne contaminants to a level that reduces the risk of infection or, in cases related to sick building, symptoms caused by other contaminants. This can be achieved by adding enough clean air with properly dimensioned air cleaners and ensuring that the devices are optimally placed in the premises. Successful risk assessment for dimensioning air cleaners requires accurate initial data on the building's ventilation system and its functionality, as well as the usage profiles of the spaces. The noise levels of the air cleaners, along with space requirements and constraints, can affect their usability. It is also important to control the use of the devices to ensure they remain active and connected while the premises are in use, so that the air cleaners work efficiently.

In this study, the risk assessment of the facilities and the dimensioning of air cleaners for daycare centers were based on several factors: the relationship between ventilation air flows and the air cleaner's output, the usage profile of the spaces, and the resulting air change rate. Weighting coefficients were calculated for different spaces, and air cleaners were strategically placed to double the amount of clean air compared to the initial situation, optimizing both effectiveness and energy efficiency. The use of the air cleaners was controlled during the health study intervention. An impact of the air cleaners on infections was compared to the results of a health study.

9.3.6 Acknowledgements

We would like to express our warm thanks to the daycare managers and personnel in Helsinki for their participation and help in implementing the intervention. We are also deeply grateful to the children and their families for their participation and patience. Additionally, we extend our sincere appreciation to the companies that provided the air cleaners for this study.

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9.4 Indoor air quality at four daycare centers in Helsinki, Finland: effect of portable air purifier units

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Abstract: Indoor air quality was studied at four daycare centers in Helsinki with air quality sensors measuring airborne particulate matter and environmental parameters, and with research-grade measurement instruments measuring particle lung-deposited surface area and particle number concentration. The effect of using portable air purifiers was evaluated with respect to particle concentrations indoors. The results show that portable air purifiers were effective in reducing airborne particle concentrations in the studied daycare centers.

9.4.1 Introduction

Airborne fine particles have direct negative health effects, resulting in various diseases and millions of premature deaths every year (Cohen et al., 2017). Exposure to them can also weaken the immune system (B. Chen et al., 2021), increasing susceptibility to infections. Furthermore, respiratory infections such as SARS-CoV-2 have been shown to spread through the air (Miller et al., 2021). Therefore, to gain a complete understanding of infection transmission, it is crucial to investigate airborne particle concentrations in areas where people gather.

Portable air purifiers offer a potential solution to reducing indoor airborne particle concentrations. They operate by recirculating room air through high efficiency particulate filters, providing particle-free air into the space. As infectious pathogens can also be transported as particles in the air, portable air purifiers may help in reducing the risk of infection through the airborne route.

In this work we monitored concentrations of airborne particulate matter in the indoor air of four daycare centres in Helsinki, Finland. During the two-year monitoring period, two interventions with portable air purifiers were carried out and the impact on indoor particulate matter concentrations was investigated. The results provide real-world data on the effectiveness of utilizing portable air purifiers in a daycare setting.

9.4.2 Methods

The study was conducted between November 7th 2022 and April 30th 2024, consisting of two intervention phases. From the beginning of the study until October 17th 2023 (intervention phase 1), two of the daycare centers were equipped with portable air purifiers while the other two operated normally. From the end of phase

1 until the end of the study period (intervention phase 2), the situation was reversed, and the air purifiers were moved to the other two daycare centers. To minimize electricity consumption, the air purifiers were switched off during the night using programmable outlets.

Indoor air quality was monitored continuously in the four daycare centers with Airlyse indoor air sensors. The sensors provide measurements on airborne particulate matter concentrations (PM_{10}, $PM_{2.5}$, PM_1), temperature (T), relative humidity (RH), carbon dioxide concentration (CO_2) and volatile organic compounds (TVOC). Three sensors were installed in each daycare providing data on different locations (playrooms, hallways, etc.).

In addition to the continuous monitoring, four measurement campaigns were conducted throughout the study period (two during phase 1, two during phase 2). During these campaigns, instruments measuring the concentration of small particles down to 10 nm (partector, naneos Ltd.) were used to gain information on the particles not detectable with the air quality monitoring sensors. Exposure to these particles may impair human immune response and is thus relevant to disease transmission (B. Chen et al., 2021). The concentration metric used here is the lung-deposited surface area concentration (LDSA).

9.4.3 Results

Figure 1 shows an example of average daily indoor PM2.5 and PM10 concentrations per hour in one daycare centre during the interventions. The upper two curves show how the PM concentrations in the daycare vary throughout the day during intervention phase 1 (air purifiers are not in operation). The lower two curves show the similar trend during intervention phase 2 (air purifiers are in operation). The results clearly show that PM concentrations are lower during intervention phase 2 when the air cleaners are on, especially during the daytime hours when the premises are occupied. The trend is similar for both PM2.5 and PM10 concentrations.

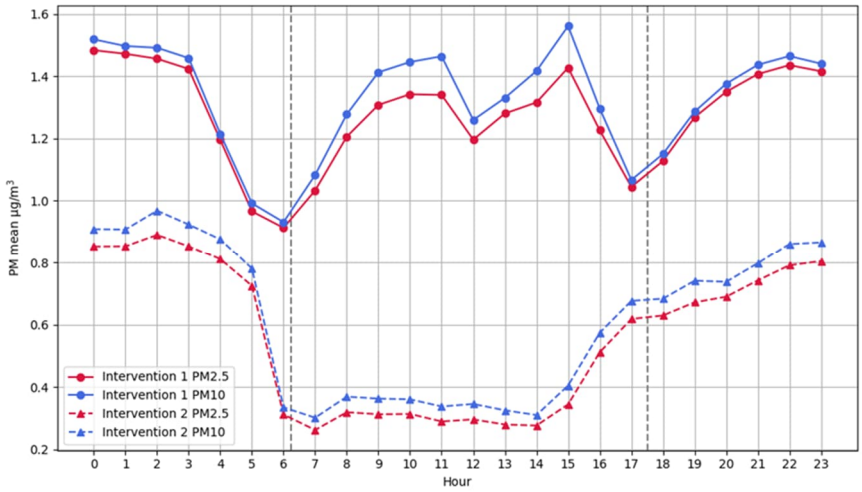

Figure 37. Average daily indoor PM2.5 and PM10 concentrations per hour in one daycare centre during the intervention phase 1 (air purifiers off) and intervention phase 2 (air purifiers on).

Figure 2 shows indoor daytime (8-16) LDSA concentration data grouped from all four daycares. The left panel represents intervention phase 1, and the right panel represents intervention phase 2. In all cases, the median LDSA concentrations in the daycares are below 4 $\mu m^2/cm^3$. This represents low concentrations typical to locations far from emission sources or indoor spaces with good ventilation and supply air filtration. During both interventions, the daycares with portable air purifiers operating (labelled “Intervention” in the graph) display significantly lower LDSA concentrations compared to the daycares without air purifiers (labelled “No intervention”). There is a reduction of 55 – 65 % in the median LDSA concentrations, when comparing the periods with and without air purifiers. This is relevant even when the concentrations are low to start with, as even low concentrations of airborne particles have been shown to have negative health effects (J. Chen & Hoek, 2020).

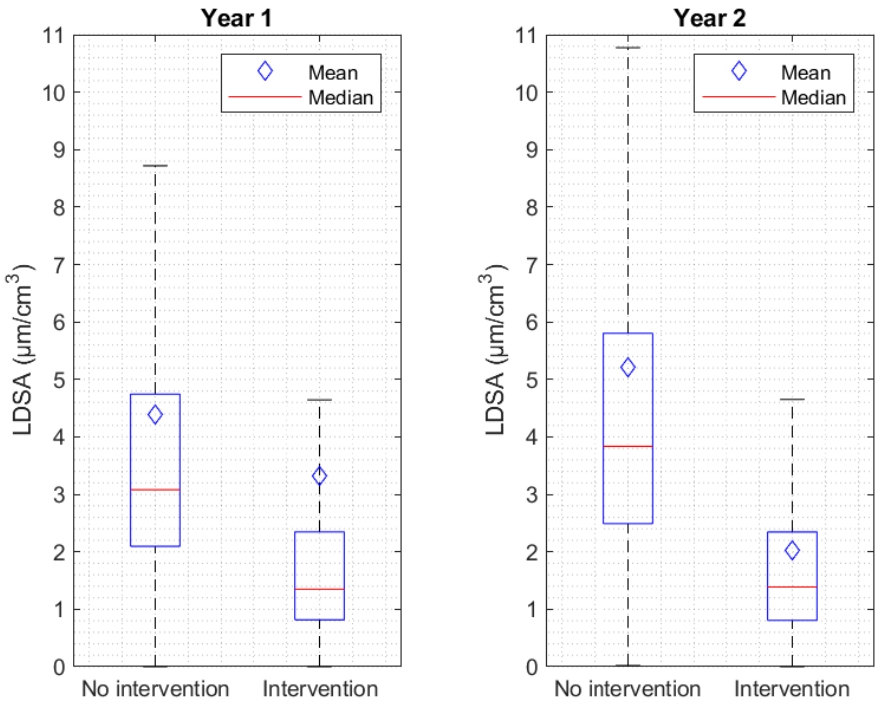

Figure 38. Daytime (8-16) lung-deposited surface area concentrations (LDSA) in the daycares during the two years of study. The left panel represents intervention phase 1, and the right panel represents intervention phase 2. Boxplots indicate the interquartile range of data with whiskers extending from the 1st and 3rd quartiles to 1.5 times the interquartile range. The red line and the blue diamond indicate the median and the mean value, respectively.

9.4.4 Discussion and conclusions

Portable air purifiers were efficient in reducing the concentration of airborne particles in the four studied daycare centres. This suggests that portable air purifiers will also remove airborne pathogens, reducing the probability of transmission. Additionally, reducing the exposure to airborne particles can inhibit inflammation in the respiratory system, thus reducing risk of transmission of pathogens transported through the air.

9.4.5 Acknowledgements

We gratefully acknowledge the help and cooperation of the daycare centre personnel, and the companies providing the portable air purifiers: Air0, Alme, Halton, ISEC and Lifa Air.

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9.5 Measurement of viruses from settled dust samples in the daycare study.

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Abstract: The objective of this work was to evaluate an approach for monitoring the occurrence of selected pathogens in daycare centers, and to assess potential effects of an air cleaning intervention. We analysed airborne dust from four daycare centers for SARS-CoV-2, Influenza A/B and Norovirus GI/GII with quantitative PCR. We detected 19% and 16% of dust samples positive for SARS-CoV-2 during year one and two of the study, respectively. Only in year two, positive dust samples clustered in the non-intervention daycares.

9.5.1 Introduction

Daycares and schools are important environments in the transmission of infectious disease agents that result in sickness absence and related economic impact. Small children have typically multiple respiratory tract infections throughout a year, and each of these episodes can last multiple days (Heikkinen et al. 2020). Sick children stay at home and require the presence of a caretaker, usually the parent or grandparent, who might need to take off from work. This has negative impacts for the affected families and results in substantial economic cost to society (Heikkinen et al. 2020). This issue, and more generally the importance of educational environments in infectious disease transmission, were highlighted during the recent COVID-19 pandemic. Infectious disease outbreaks are common challenges in daycare centers even in the absence of an on-going pandemic, calling for approaches to monitor and reduce pathogen occurrence in daycares.

Traditionally, hand-, coughing- and overall hygiene, and regular cleaning of indoor surfaces are among the common disease transmission preventive measures in daycare centers, importantly alongside vaccination programs and the requirement of sick children or teachers to not attend the daycare. Infectious diseases that have also a strong aerosol transmission component further challenge buildings to function well, especially on the aspect of effective and sufficient ventilation. Ventilation of indoor spaces is also important in keeping indoor pollutants, for which sources cannot be effectively controlled, at levels that are not detrimental to human health. Portable air cleaners have long been assessed as engineering solutions to reduce levels of harmful pollutants from indoor air, including microbial components. During the COVID-19 pandemic, air cleaners were widely discussed and promoted globally as a way to reduce infectious disease transmission in educational environments, despite limited

understanding of their effectiveness. Still today, knowledge on the performance of air cleaners to remove specific microbes from indoor air is largely based on chamber studies carried out under highly controlled conditions (Ueki et al 2022). Such studies are useful and relevant, but do not translate into the actual effectiveness of air cleaning interventions in real-life, occupied indoor spaces, where their effects on airborne microbial levels and transmission risk are unclear (Banholzer et al. 2023).

Wastewater-based surveillance of SARS-CoV-2 has proven useful and valuable in efforts to monitor COVID-19 at the community level, in particular in situations where clinical testing capacity is limited. While data from wastewater surveillance on levels of virus circulating in the population does not equal the number of infected people, such information allows following trends and anticipating onset and progression of new epidemics. Wastewater monitoring can reasonably be applied to various pathogens and for example in Finland, influenza viruses A and B and respiratory syncytial virus (RSV) are currently monitored alongside coronaviruses. Monitoring approaches similar to wastewater surveillance are not available for indoor environments, despite the fact that very similar benefits could be gained through such effort. Following changes in infectious disease agent occurrence and levels in public buildings could help in anticipating outbreaks. Such monitoring would also allow assessing the effectiveness of measures that are implemented to reduce infectious disease transmission, such as ventilation or air cleaning interventions. In this context, public buildings, such as daycare centers, schools and offices, are of particular interest.

The key objectives of this work were two-fold: first, to evaluate whether the occurrence of infectious disease agents in daycare centers and the prevalence of sickness absence of daycare children can be monitored through indoor environmental sampling of settled dust and targeted microbe measurements; and second, to study the impact of an extensive portable air cleaner intervention on the occurrence of specific virus groups in daycare classrooms. With this research we set out to answer following study questions: Can indoor airborne dust be used as a sample matrix to monitor occurrence and levels of certain pathogens in daycare centers? Do portable air cleaners reduce indoor pathogen occurrence and/or levels in settled dust of daycare centers? And does pathogen occurrence in settled dust correlate with sickness absences among daycare pupils?

9.5.2 Research design and Methods

A detailed description of the study design and all the measurements conducted in the daycare study trial can be found at the beginning of this chapter in this report (Sormunen and Vartiainen). The following represents a short summary of the key aspects relevant to the current paper.

Study design

This study was conducted in four daycare centers in the city of Helsinki and was implemented as a cross-over trial over two winter seasons, in which two randomly

selected daycares (A and B) followed an Intervention (year 1) – Control (year 2) sequence, and daycares C and D followed the opposite sequence. The daycares were chosen to be located within a close geographic area and in the same neighbourhood in the city of Helsinki, and to be rather similar in terms of age, key building characteristics and size (between 85 and 123 children). All daycares were comparably newer buildings with modern HVAC systems, including full mechanical ventilation (providing HEPA filtered in-coming air) and heat recovery modules without air recirculation.

The actual intervention consisted of adding portable air cleaners into all daycare classrooms and the majority of other commonly used indoor spaces in the daycare centers, including eg. the hallways, sleeping and eating areas, or sports halls. The aim was to assist the basic ventilation system and increase the clean-air delivery rates in these spaces. A total of 45 air cleaners were used and operated during daytime. The different air cleaner models had particulate clean air delivery rate (CADR) between 125 m^3/h to 1500 m^3/h. More detail on considerations of placement and dimensioning of the portable air cleaners in the individual rooms are provided elsewhere in this chapter.

Environmental sampling and sample processing

For the downstream analyses of selected virus targets we collected continuously airborne, settling dust (particulate matter) over three-week sample accumulation periods, following the approach described by Adams et al. (2015). In brief, airborne dust was collected passively with sterile petri dishes placed at a height of 150-250cm, typically on the top of cupboards or shelves, at locations that were not affected majorly by air flows coming for example from windows, doors, ventilation ducts or similar (Figure 1). In each daycare center, five class/playrooms that were commonly used were selected for the sampling of settled dust. In addition, airborne particulate matter was also collected outdoors using this same petri-dish approach and a weather resistant casing. Sampling locations in all four daycare centers stayed the same throughout the two sampling periods.

During year one, dust samples were collected during seven three-week periods between November 2022 and April 2023; during year two, dust samples were collected during nine three-week periods from October 2023 to April 2024. In total, we collected 320 indoor dust samples from 20 daycare class/playrooms in four daycares over 16 three-week periods.

Figure 39. Example location for collection of airborne, settling dust with sterile petri dishes as passive dust collectors in a daycare classroom.

In each location, six petri dishes were used for the dust collection (Figure 1), providing material for three subsamples that were used for downstream DNA extraction, RNA extraction, and a bio-banked back-up sample. For each of these subsamples, two petri dishes were thoroughly swabbed to remove the particulate matter with a FloqSwab (Copan Diagnostics) wettened in suitable buffer (sterile water + 0.05% Tween20 for DNA samples; DNA/RNA shield solution (Zymo Research) for RNA and back-up samples). Samples were stored at -80C until further processing.

Quantitative PCR (qPCR) analyses of selected virus targets

The settled dust samples collected as described above were used for targeted analysis of viruses SARS-CoV-2, Influenza A and B, and Norovirus genotypes GI and GII, using quantitative PCR. The protocol for RNA extraction, cDNA synthesis and subsequent qPCR analysis is described in detail in this report in the section authored by Valkonen et al.. The key steps are briefly summarized in the following.

The RNA extraction was performed using Chemagic Vial300 DNA/RNA Kit (PerkinElmer) on a Chemagic 360 instrument (Revvity), following an initial 2-minutes vortexing step of the FloqSawbs in 600µl lysis buffer provided in the extraction kit. cDNA synthesis was performed using the Superscipt IV Vilo Mastermix (Invitrogen). The quantitative PCR analyses for selected virus targets included: N1 assay detecting the N-gene in SARS-CoV-2 virus (Lu et al. 2020); Inf-A and Inf-B assays as described in the webpages of the US Centers of Disease Control (CDC; https://www.cdc.gov/coronavirus/2019-ncov/lab/multiplex.html) for the detection of Influenza A and B strains using primer and probe sets InfAFor1/InfARev1/InfA-P1 and InfBFor1/InfBRev1/InfB-P1, respectively; and norovirus GI (primers/probe: NVGIF/NVGIR/NVGIP-MGB) and

GII (QNIF2d/ COG2R/P1) assays for the detection of strains of these two genotypes, using an optimized protocol base on Kauppinen et al. (2014).

9.5.3 Results and Discussion

We present and discuss here the results of targeted virus analyses using qPCR on 320 three-week integrated settled dust samples, collected from 20 daycare classrooms located in four daycare centers in Helsinki. Much of this presentation centers around the detection of SARS-CoV-2 in the daycare dust samples, due to the obvious interest in this group of viruses and its dominant presence in the population during the sampling seasons 2022/2023 and 2023/2024. This is reflected in a relatively high prevalence of SARS-CoV-2 in daycare dust samples: in total, 56 samples were tested positive, which translates into 18% of all daycare dust samples. The positive samples were quite evenly distributed between year one (n=27, 19%) and year two (n=29, 16%) (Table 1). In contrast, Influenza A and B were detected very rarely in the daycare dust samples, i.e. in one and three samples, respectively, which is less than 1% of samples in either case. Noroviruses were analysed only in year two samples, in which genotype II virus was detected more frequently (7.8%) in dust samples compared to genotype I (2.8% of positive samples) (Table 1).

Table 1. Overview of the numbers and percentages of samples detected positive for the different virus targets. Results are split by year and are shown for the individual daycare centers, for all daycare centers combined, as well as for the intervention and non-intervention daycare centers separately.

		Number and percentage (%) of samples positive for the respective target virus						
		D1	**D2**	**D3**	**D4**	**All Daycares**	**Inter-vention**	**Non-intervention**
SARS-CoV-2	yr 1	10 (29%)	1 (2.9%)	13 (37%)	3 (8.6%)	27 (19%)	16 (23%)	11 (16%)
	yr 2	3 (6.7%)	2 (4.4%)	15 (33%)	9 (20%)	29 (16%)	5 (5.6%)	24 (27%)
Inf A	yr 1	0	0	0	0	0	0	0
	yr 2	0	0	1 (2.2%)	0	1 (0.6%)	0	1 (1.1%)
Inf B	yr 1	1 (2.9%)	0	0	0	1 (0.7%)	0	1 (1.4%)
	yr 2	1 (2.2%)	0	1 (2.2%)	0	2 (1.1%)	1 (1.1%)	1 (1.1%)
Noro GI	yr 1	NA	NA	NA	NA	NA	NA	NA
	yr 2	1 (2.2%)	1 (2.2%)	2 (4.4%)	1 (2.2%)	5 (2.8%)	2 (2.2%)	3 (3.3%)
Noro GII	yr 1	NA	NA	NA	NA	NA	NA	NA
	yr 2	5 (11%)	1 (2.2%)	5 (11%)	3 (6.7%)	14 (7.8%)	6 (6.7%)	8 (8.9%)

Class-room	Day-care	Inter-vention	SARS-CoV-2, 2022/2023						
			wk 48-50	wk 51-01	wk 02-04	wk 05-07	wk 08-10	wk 11-13	wk 14-16
C1		no							
C2		no							
C3	D1	no							
C4		no							
C5		no							
C6		no							
C7		no							
C8	D2	no							
C9		no							
C10		no							
C11		yes							
C12		yes							
C13	D3	yes							
C14		yes							
C15		yes							
C16		yes							
C17		yes							
C18	D4	yes							
C19		yes							
C20		yes							

Figure 40. Detection of SARS-CoV-2 RNA in airborne particulate matter of 20 daycare classrooms from four daycare centers during 2022/2023 (year one). Daycares 1 and 2 were operated without and D3 and D4 with portable air cleaning intervention. Yellow colour indicates SARS-CoV-2 detection in a specific sample, green colour absence of the virus in the sample.

Moving on to evaluating the impact of the air cleaning intervention on detection of viruses in the daycare dust we present the results of SARS-CoV-2 detection in the individual classroom samples for year one in Figure 2 (seven samples from consecutive three-week integrated dust samples for each room) and for year two in Figure 3 (nine samples from consecutive three-week integrated dust samples for each room). In year one, 16 positive dust samples (23%) were detected in intervention daycares, and 11 positive samples (16%) in non-intervention daycare (Figure 2; Table 1). While we did not observe any obvious impact of the air cleaning intervention on virus detection in daycare dusts, there are two daycares – D1 (no intervention), D3 (intervention) – where disproportionally many dust samples were positive for SARS-CoV-2 (29% and 37%), whereas in daycares D2 and D4 the virus RNA was detected only in few samples (2.9% and 8.6%).

Evaluating the SARS-CoV-2 measurements from the year two samples (Figure 3) we observed that the majority of virus positive samples were collected in non-intervention daycare classrooms (n=24 positive samples; 27%) compared to intervention classrooms (n=5 positive samples; 5.6%). The pattern is also different from year one in that most positive samples were detected in the end of 2023, and only few samples in early 2024, whereas in year one positive samples were found

throughout the observation period from fall 2022 to spring 2023. In both years it was often the case that the virus was found during the same period in several classrooms in the same daycare, indicating a more widespread presence of the virus in that daycare center during that particular period. Another observation was that in year one, SARS-CoV-2 was detected in two classrooms (C11 and C13) in five consecutive sample, i.e. over a period of 15 weeks. It is unclear whether this indicates persistence of the virus in the dust over longer periods of time, which is less likely as such long-term detection in a classroom was rather rare, or rather recurrent introduction of virus over time through several infected daycare occupants.

Norovirus detection was evenly distributed between intervention (6.7% positive samples) and non-intervention (8.9% positive samples) classrooms in the year two samples (Figure 4). We did see clusters of samples, i.e. virus positive samples in multiple classrooms of the same daycare at the same time, and/or in subsequent samples in the same classrooms, possibly pointing towards norovirus outbreaks in the daycare centers.

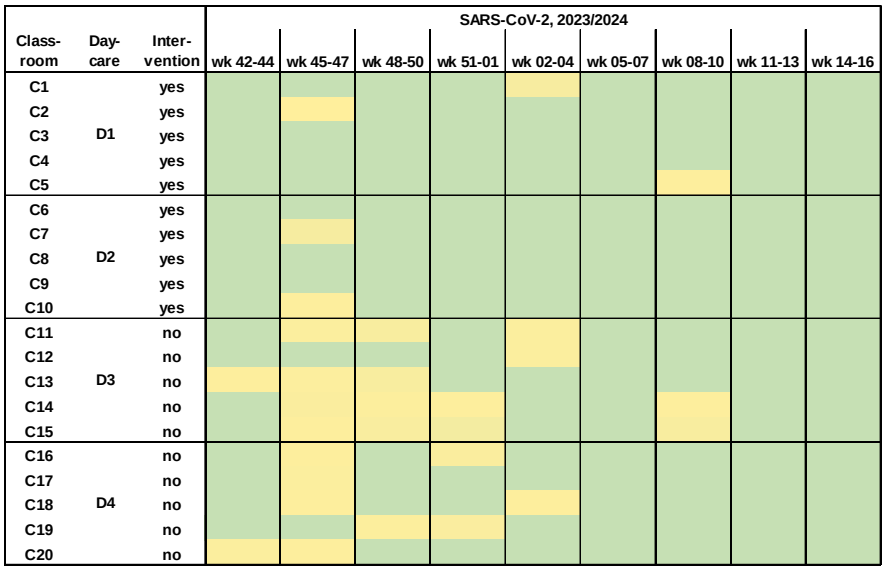

Figure 41. Detection of SARS-CoV-2 RNA in airborne particulate matter of 20 classrooms from four daycare centers during 2023/2024 (year two). Daycares 1 and 2 were operated with and D3 and D4 without portable air cleaning intervention. Yellow colour indicates SARS-CoV-2 detection, green colour the absence of the virus in the sample.

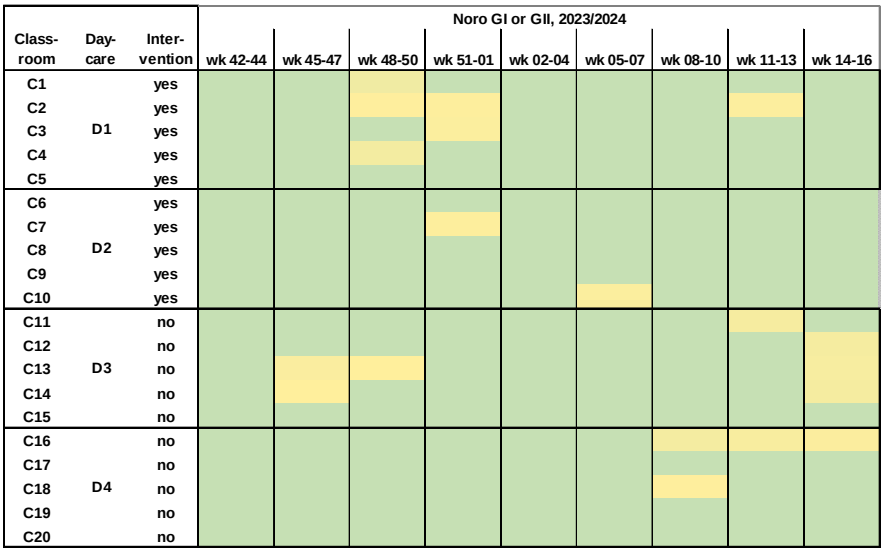

Figure 42. Detection of norovirus genotype I or II viruses in airborne particulate matter of 20 daycare classrooms from four daycare centers during 2023/2024 (year two), with and without air cleaning intervention. Yellow colour indicates norovirus detection, green colour the absence of the virus in the sample.

9.5.4 Outlook and Conclusions

This report is restricted to a descriptive presentation of the study results on detection of targeted virus groups in daycare dust samples in the context of an extensive air cleaning intervention. One of the key findings was that SARS-CoV-2 RNA was regularly detected, in almost one fifth of all daycare dust samples, indicating the potential of using airborne, settling dust collected from elevated surfaces as a sample matrix for monitoring virus occurrence in daycare classrooms. It is important to note that the presence of virus RNA does not equal the presence of *infectious* virus – such measurement would require a cultivation-based viability assessment rather than targeting RNA with quantitative PCR. The second key finding relates to the impact of air cleaning on the detection of virus in daycare dust: while during year one there was no obvious effect of the intervention on virus detection, and we rather observed differences in virus prevalence for two of the four daycare centers irrespective of the air cleaning intervention, year two was different in that virus-positive samples clearly clustered in the non-intervention daycare centers. There is no simple explanation for this observation, and only in-depth analyses of the data, including different potential confounders, such as occupancy and clean air delivery rates in the individual classrooms, will offer potential answers. We are currently compiling an extensive dataset for a thorough statistical analysis of the data, which

will then be summarized as a scientific journal publication. The fact that the full dataset is still to be compiled and analysed is also the reason for why no statistical test results are presented here and we restricted to a descriptive presentation. Future analysis efforts will also involve sickness absence data from the four daycare centers, which will enable us to answer following questions: Do portable air cleaners reduce indoor pathogen occurrence in settled dust of daycare centers? And does pathogen occurrence in settled dust correlate with sickness absences among daycare pupils?

9.5.5 Acknowledgements

We wish to thank the molecular microbiology laboratory at former Indoor Environments team at THL, in particular Heli Martikainen, Katja Saarnio, and Mervi Ojala, for excellence in sample processing and analyses.

9.5.6 References

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9.6 Ambient air quality in suburban area and preliminary assessments of its influence to indoor air quality

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Abstract: A Vaisala AQT530 sensor was used to study the air quality (PM2.5, PM10, SO2, NO, NO2, CO, O3) at the daycare for approximately the period of the daycare study (13.2.2023- 15.6.2024) and Airlyse sensors in indoor (1.6.2023-15.6.2024). The results were compared to both indoor air quality results and particle number concentration measurements conducted mobile measurements with the Atmo-Lab mobile laboratory. In this article we show main findings from the outdoor air quality measurements with Vaisala AQT sensor, some results from mobile lab measurements, and preliminary comparisons of outdoor (AQT) and indoor (Airlyse) measurements.

9.6.1 Introduction

World health Organization (WHO, 2021) recently estimated that air pollution annually causes 7 million premature deaths and the loss of hundreds of millions of healthy years. In urban areas, the ambient air contains a complex mixture of pollutants with variable concentrations, composition and sources (Barreira et al., 2020). Ambient pollution can be transported from outdoors to indoors e.g. via open windows, leaks in buildings and ventilation systems. Therefore, it is utmost important to consider the outdoor air quality when new buildings are being designed.

Stationary measurements either by standalone setup or an air quality station housing a variety of instruments give a comprehensive view of air quality in a certain location over long period, whereas the benefit of mobile measurements is the ability to study spatial and temporal variation of pollution in the whole area (Rönkkö et al., 2017). Additional measurements in indoor conditions are needed in order to study the influence of the outdoor air to indoor air quality.

The aim is to study how much outdoor air pollution affects the indoor air quality and what kind of measurements are needed to demonstrate the impact. In this article we show main findings from the outdoor air quality measurements with Vaisala AQT sensor, some results from mobile lab measurements, and preliminary comparisons of outdoor and indoor measurements.

9.6.2 Research design/Experimental

To study air quality in the area, we utilized a combination of stationary and mobile measurements in ambient conditions as well as sensor type measurements in indoor conditions. The measurements were conducted inside a daycare in Helsinki, stationary measurements in the backyard of the daycare and mobile measurements in the urban areas surrounding the daycare.

Stationary air quality measurements were conducted outside the daycare situated in Helsinki. During the daycare study (13.2.2023- 15.6.2024) AQT530 sensor was used to measure the ambient concentrations of selected gaseous and particulate pollutants and meteorological parameters. The measured gases were NO, NO_2, CO, and O_3. The AQT530 sensor gave also the particle mass of PM_1, $PM_{2.5}$, and PM_{10}. For gas measurements AQT530 utilizes electrochemical gas sensor technology. By using algorithms, factory calibration, and parts per billion (ppb) concentrations at different environmental conditions can be measured. Particles are measured with a laser particle counter (LPC). Single particles scatter light and based on the scattered intensity and number of pulses detected, the particle sizes and mass concentrations are calculated. The measured meteorological parameters were air temperature, air pressure, and relative humidity. The time resolution of the measurements was one minute.

Mobile measurements were conducted to get detailed information about the air quality in the area. The measurements were carried out in two parts in the spring and fall of 2023, using the Aerosol and Trace-gas Mobile Laboratory (ATMo-Lab) from Tampere University. The measured parameters were total number concentration (PNC), size distributions (PSD), lung-deposited surface area concentration (LDSA), chemical composition and black carbon (BC) concentration of particles. Gas-phase nitrous oxides (NOx) and carbon dioxide (CO2) were also measured. Each campaign consisted of driving measurements and stationary measurements. On stationary measurement days, the ATMo-Lab was parked near the day care center from 8:00-17:00. On driving measurement days, the route was circulated between approximately 8:00-11:30 and 12:30-17:00. Figure 1 shows the two different driving routes used in the measurements. During lunch on driving measurement days, the ATMo-Lab was parked near a day care center. In total, there were 10 days of driving measurements and 8 days of stationary measurements.

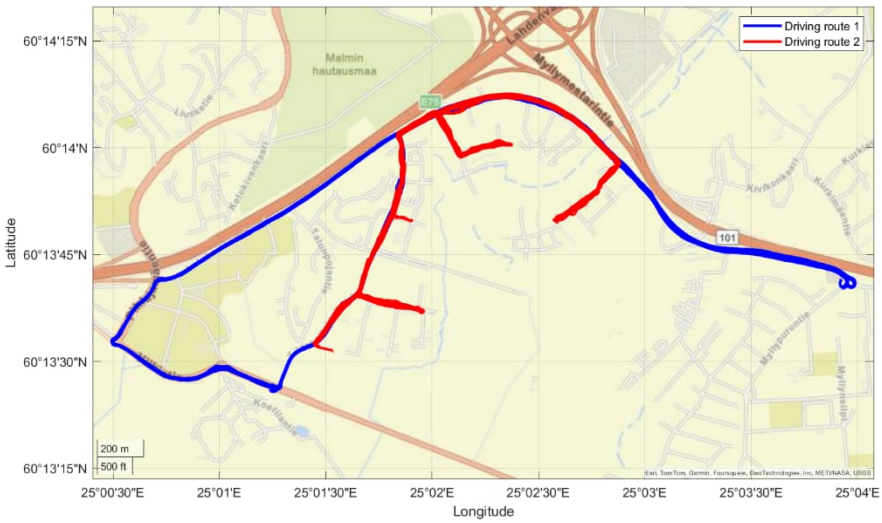

Figure 1. The driving routes during the mobile measurements.

Indoor measurements were conducted with AirLyse sensors that were placed in the intervention rooms to monitor temperature, humidity, carbon dioxide, fine particulate matter (PM1, PM2.5, PM10), CO2 and TVOC.

9.6.3 Results

Ambient air quality was monitored via stationary and mobile measurements**.** Stationary measurements showed that in general the ambient air quality in the studied urban area was good. The average PM2.5 concentration during the measurement period was 1.9 ± 2.1 (average ± St.Dev), which is a typical concentration in urban environment in Finland. Figure 2 shows a timeseries and figure 3 shows the daily, monthly and weekday variation of PM1, PM2.5 and coarse particles (PM10-PM2.5) measured in ambient conditions near the daycare. During the road dust season (March-April), some increases were seen in coarse particle concentrations, but otherwise the concentrations for all size fractions were relatively low (<10g m-3).

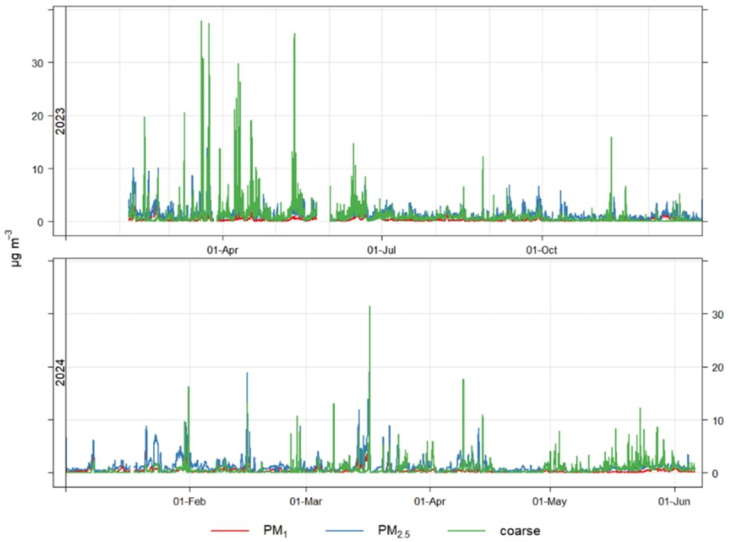

Figure 2. The concentrations of ambient PM1, PM2.5 and coarse particles (PM10-PM2.5) during the measurement period

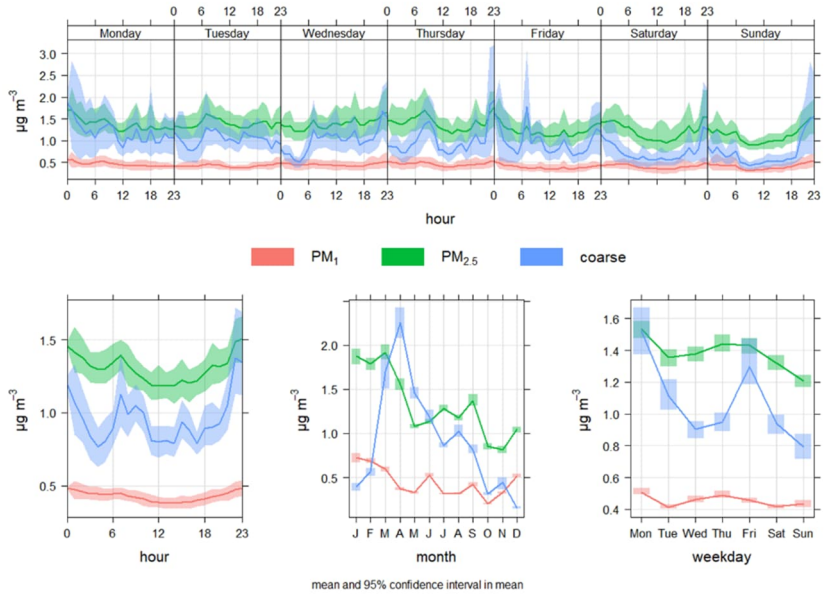

Figure 3. The monthly (left) and daily average (right) concentrations of ambient PM1, PM2.5 and coarse particles (PM10-PM2.5) during the measurement period.

In addition to particles, the AQT sensors were measuring concentrations of several trace gases (NO, NO2, CO, O3). Figures 4 and 5 show the diurnal, monthly and weekday variation of NO, NO2 and CO. Nitrogen dioxide (NO2) is a tracer of traffic emissions, whereas carbon monoxide (CO) is originating both from traffic and biomass combustion (e.g. wood burning). A clear diurnal cycle with maximum during daytime when traffic volumes were highest was observed for NO2 concentrations in the area. CO had spikes during the rush hours but also at evenings, especially during weekends, likely due to both traffic and biomass combustion emissions.

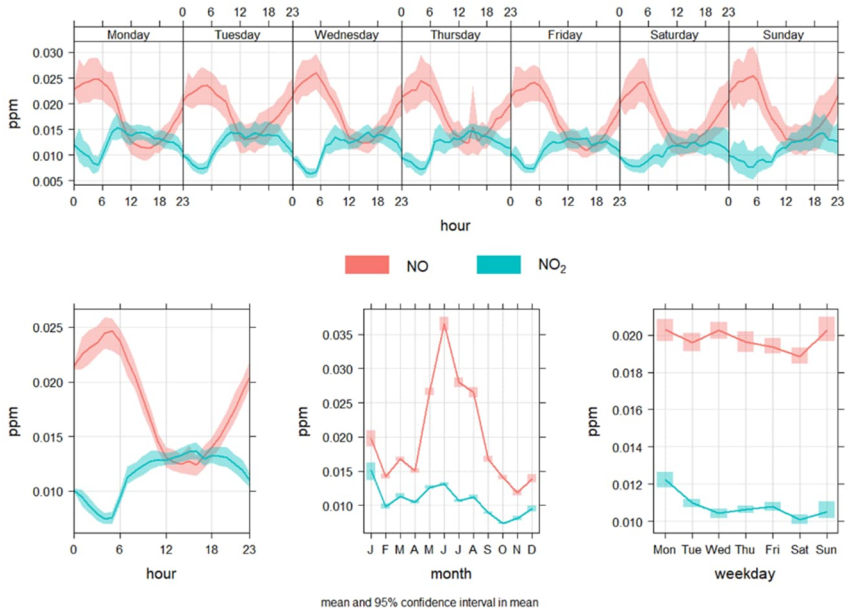

Figure 4. The daily, monthly and weekday variation of ambient NO and NO2 during the whole measurement period.

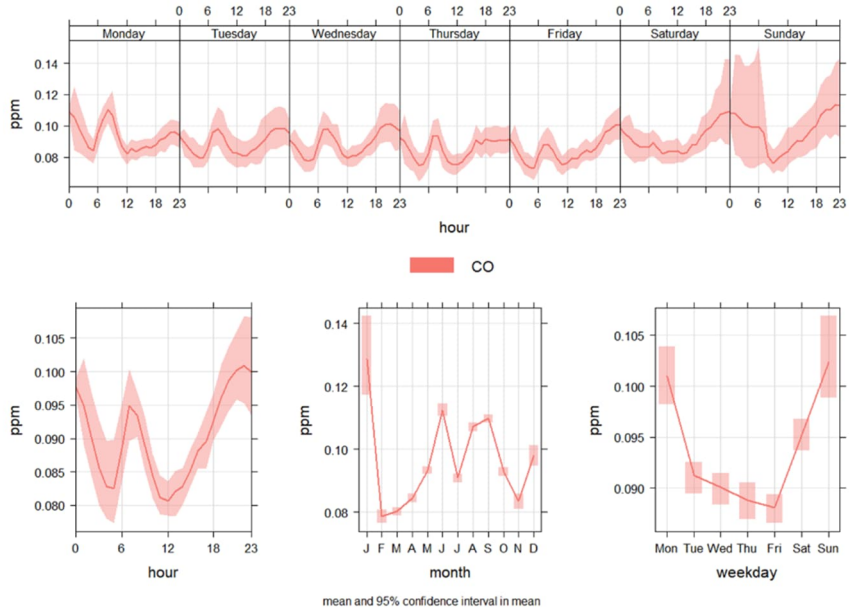

Figure 5. The daily, monthly and weekday variation of ambient NO and NO2 during the whole measurement period.

Figure 6. shows the measured outdoor particle number concentrations in the area near the day care centres. Median particle number concentrations were between 5000 – 35 000 1/cm3, with a decreasing trend when moving further away from the nearby highway.

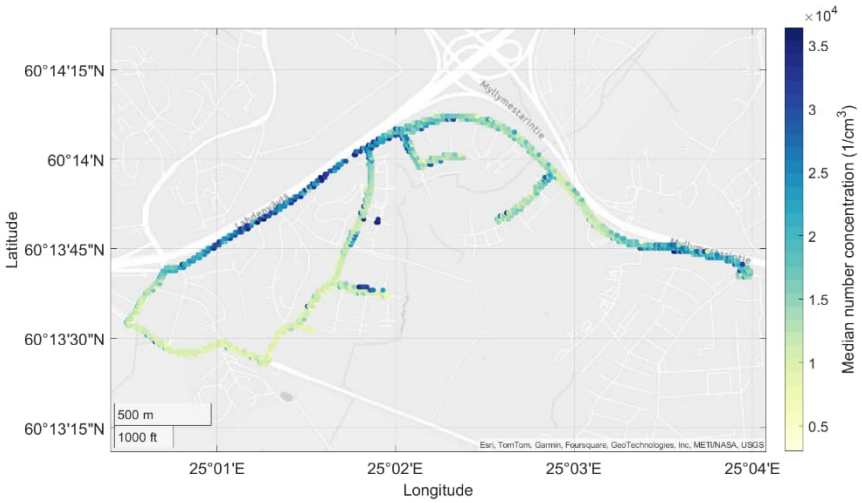

Figure 6. Median particle number concentrations in the area near the day care centres. The darker coloured points represent higher and lighter points lower concentrations.

Indoor air quality and its correlation with ambient air quality was a special focus during the intervention periods.

Figure 7. shows correlation between PM2.5 concentrations measured in outdoor and indoor conditions. It can be seen that the higher the ambient concentrations are related to elevated concentrations in indoors also.

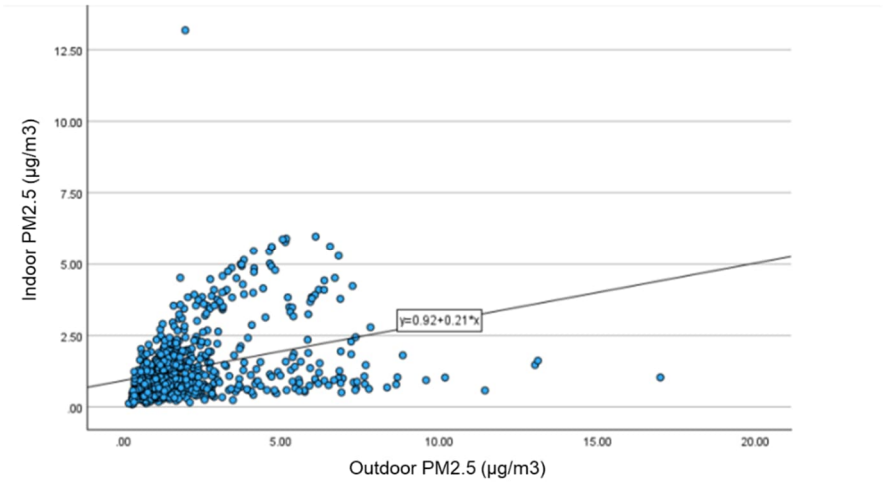

Figure 7. Correlation between outdoor PM2.5 and indoor PM2.5 measurements in a daycare centre from 6.2.2023-30.4.2023.

9.6.4 Conclusions

In general, outdoor air was fairly clean near the daycare and the observed particle mass concentrations in all size fractions were fairly low. The influence of nearby roads and biomass combustion in residential areas was seen in the ambient PM2.5, NO2 and CO concentrations.

Mobile measurements in area showed a clear variation of particle number concentrations in different urban environments. Median particle number concentrations were between 5000 – 35 000 1/cm3, with a decreasing trend when moving further away from the nearby highway.

When comparing the indoor and outdoor measurements, a relationship between ambient PM2.5 concentrations and indoor PM2.5 was seen, highlighting the importance of considering the outdoor air quality in city planning.

9.6.5 Acknowledgements

We gratefully acknowledge the help from the daycare personnel during the measurement campaigns.

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10 Concluding remarks

10.1 Industry benefits of the E3 project

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Abstract: One objective of the E3 Pandemic Response co-innovation project was to develop research-based solutions to prevent the spread of pathogens, e.g. SARS-CoV-2, and ensure the continuity of different societal functions during pandemics. Key findings showed that air cleaning effectively reduces airborne transmission and improves indoor air quality. The project's industry-research collaboration also led to innovative technical solutions and new business models.

10.1.1 Introduction

Launched in 2021, the Excellence in Pandemic Response and Enterprise Solutions (E3) co-innovation project aimed to meet the urgent need for research-based solutions to prevent the spread of pathogens and fight the then-dominant COVID-19 pandemic. The primary focus was to study different pathways of pathogens and viruses, virus control, and detection methods. One main goal was to develop solutions that allow society's various functions to continue without interruption despite epidemics and pandemics.

As a co-innovation project, a key part of the E3 Pandemic Response project was to build systematic industry-research collaboration to tackle the research challenges defined, foster pandemic-tackling innovations and test different solutions in real-life settings (Figure 1). The multidisciplinary E3 project consortium included 7 research organizations and 22 industry partners from different fields. Research organisations represented medicine, microbiology, aerosol physics and technology, smart buildings, industrial technology, business models, and

behavioural science. Industry partners involved in the project were specialized e.g. in environmental monitoring, medical diagnostics, system integration (including building technology), real estate and construction, air cleaning solutions, infection control and people flow.

A key platform for the industry-research collaboration in the E3 project was three use cases conducted in hospital, office (built laboratory setup) and daycare settings. The use cases, presented in-depth in the previous chapters, served as piloting environments for validating the scientific results through proof-of-concept studies and testing the applied research findings together with various company solutions. Through this hands-on joint development, the project partners gained understanding of the viability of various innovative solutions, built new partnerships and networks, and brought new insights into real customer needs.

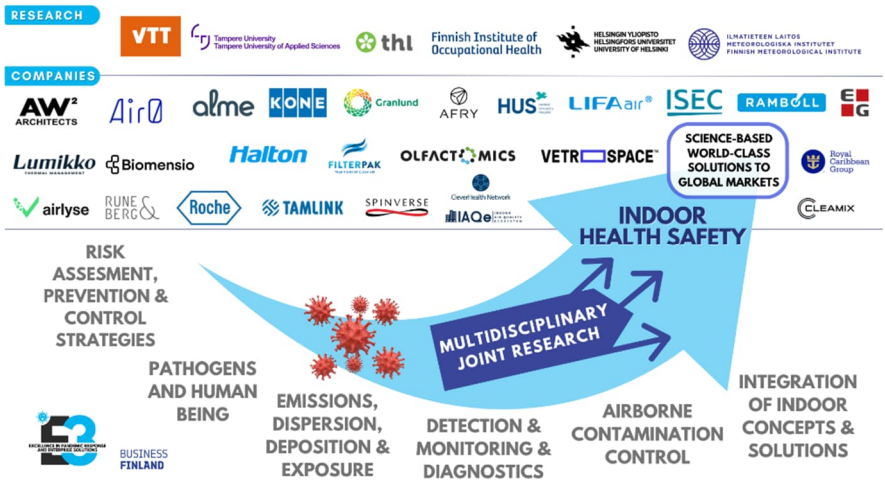

Figure 43. The E3 Pandemic Response co-innovation project has a collaborative structure. Research and industry partners contributed to reach the objective of science-based world-class solutions to global markets.

In this paper, some of the research highlights of the E3 project are discussed from the industry point of view.

10.1.2 Increasing clean air delivery reduces exposure to pathogens

The prevailing hygiene paradigm, especially before the COVID-19 pandemic, focused on preventing transmission through droplets and direct contact. This view was challenged as mounting evidence during the first year of the pandemic confirmed the significant role of airborne transmission in the spread of SARS-CoV-2. The E3 project studied the airborne transmission route through applied research and tested industry partners' solutions for mitigating the risks of airborne infection.

One important research result obtained in the E3 project was that cleaning indoor air can significantly reduce morbidity. This result was primarily achieved by using various air cleaners to produce more clean air to the premises. The findings demonstrated that air cleaners effectively lower airborne particle concentrations across different environments, helping to reduce the risk of respiratory infection transmission. A key finding, crucial especially for the users and buyers of air cleaners, is that for optimal results the clean air delivery rate (CADR) of air cleaners needs to be matched to pathogen emissions and the existing ventilation levels in the premises.

The research also demonstrated that the functionality of the ventilation system plays a crucial role in preventing the spread of airborne diseases. Therefore, the ventilation system must operate as designed from a health-safety perspective. Findings from the E3 project showed that increased ventilation and air cleaning can effectively mitigate the airborne transmission of infectious diseases. The E3 project also demonstrated how infection risks can be assessed for different indoor spaces, and tailor the solutions based on actual needs. This knowledge is valuable not only during pandemics but also for reducing the spread of influenza and other common respiratory illnesses to increase productivity and well-being. Scientifically validated solutions already exist, offering effective tools to improve public health. Increased attention to the use of these technologies could lead to healthier indoor environments, benefiting individuals, societies, and industries by reducing illness and improving overall well-being and productivity.

10.1.3 Diagnostics and medicine

Medical research was an essential part of the E3 project, to address the question of how a healthier and safer indoor environment could be implemented in the future. Medical research created a solid scientific basis for the multidisciplinary research approach, providing access to the relevant hospital infrastructure, and bringing important new knowledge, especially in diagnostics. The joint work involved e.g. diagnosing different pathogens from people but also from the environment. The collaboration brought a unique opportunity to use the newest commercial diagnostics tests for analyzing a wide set of samples and sample types.

During the E3 project, nasal and saliva samples, which are more comfortable to people than the traditional sampling, were shown to have high potential. Serum and plasma samples were also evaluated and compared with the currently used nasopharyngeal sampling. This brought important evidence on the usability of the new tests and different sample types for diagnosing a variety of different pathogens.

Other studies focused on collecting viruses from indoor air through settled dust and studying volatile organic compounds (VOC) generated by viruses. As different viruses produce a so-called unique VOC signature, this could be used to distinguish between different respiratory infections. The results demonstrated that VOC analysis has the potential to differentiate between respiratory viruses,

offering a non-invasive and real-time diagnostic tool for human beings or even for environment analysis.

10.1.4 New innovative products and services to keep societies open during future pandemics

One of the goals of the E3 project was to develop new solutions that allow various functions of society to continue without interruption and for people to live safely despite epidemics and pandemics. To envision new solutions, the industry partners have utilized the E3 consortium's research knowledge and brought their know-how and insights into the use cases to test solutions in real-life settings.

From a business perspective, the E3 project has enabled e.g., the development of new business models for property owners, such as workplace consultation and space utilization monitoring services. Additionally, the E3 project has provided a platform for specific collaboration between different companies. As a result of such collaboration, e.g. an innovative decontamination device was created to clean air, surfaces, and materials, thereby preventing the spread of viruses and bacteria in various environments.

The industry-research collaboration also advanced the understanding of micro-environments, aimed at improving indoor air quality on a localized level. The objective was to create specific zones within a room with improved air quality and thus decreased infection risk. The findings of the E3 project's micro-environment studies, conducted in a laboratory setting, demonstrated that solutions used to create these controlled micro-environments reduced aerosol exposures at the personal breathing zone more than in the overall room environment. These solutions, which create micro-environments, offer promising approaches and tools for improving indoor air quality, especially in areas, where people spend time the most, e.g. office workstations.

In the hospital use case, the E3 project demonstrated that a regular patient room can be converted into an isolation room by using an air cleaner. Studies showed that clean air delivery achieved nearly the same threshold values as those designed for ventilation in newly constructed isolation rooms. By increasing the production of clean air, it is possible to protect the patient or, conversely, the environment and staff from the patient. This has significant implications globally for existing hospital environments in mitigating the spread of airborne diseases.

Thus, the extensive and truly multidisciplinary scientific research work in the E3 project has advanced the understanding of pandemics and the needed countermeasures to fight them. This new, comprehensive knowledge has already enabled industry partners to develop solutions in areas such as environmental sensing, monitoring and medical diagnostics to specific clean-air solutions and services regarding different spaces. Due to confidentiality, specific solutions are not described in detail in this public report. As the E3 project's versatile findings and new know-how have only recently been disseminated to companies, we expect it to enable new product and service development leading to significant new business opportunities in the future.

10.1.5 Conclusions

In summary, the industry partners involved in the E3 project, particularly those participating in the different E3 use case environments, achieved important results that can be applied in their business operations. The feedback and data collected from pilot hosts (such as hospitals and daycare centers) have brought valuable knowledge both for service and product development. Additionally, research on pathogen spread and control has played a critical role in advancing technologies that not only help prevent the transmission of infectious diseases across different indoor settings but also enhance indoor air quality.

After the E3 project, the challenge remains in effectively promoting these solutions and helping potential key decision-makers, recognize their benefits and take the new solutions into use. During the COVID-19 pandemic, there was a significant market demand for scientifically proven solutions to mitigate the spread of SARS-CoV-2. However, as the urgency of the pandemic decreased, the interest declined. Nevertheless, these solutions remain crucial, as they can be used to reduce the spread of influenza and other common respiratory illnesses, offering tangible benefits for public health. The results of the E3 project can also help employers compete for top talent in the market by providing employees with responsible and comfortable spaces that enhance productivity and well-being. Given that the average cost of a single sick leave day to employers and society in Finland is estimated to be around 420 euros (Työterveyslaitos 2024), reducing the transmission of respiratory illnesses also holds the potential for substantial cost savings for society.

The new knowledge and solutions created in the E3 project have enhanced preparedness for both future pandemics but also seasonal respiratory illnesses, strengthening societal resilience. By adopting these innovations, societies can protect public health, improve productivity, and ensure long-term competitiveness in a rapidly changing world.

10.1.6 Acknowledgements

The following companies were involved in the E3 Pandemic response co-innovation project:

Monitoring and diagnostics:
Airlyse Oy, Biomensio Oy, Helsinki University Hospital (HUS), Olfactomics Oy and Roche Diagnostics Oy.

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AW2 Architects Oy, AFRY Finland Oy, Granlund Oy, EG Finland Oy, Halton Oy, Ramboll Oy.

Clean air solutions:
Air0 Oy, Alme Solutions Oy, Filterpak Oy, Inspector Sec Oy, Lifa Air Oy, Lumikko Oy, Vetrospace Oy.

People flow and infection control:
Cleamix Oy, Kone Oyj, Royal Caribbean Group, Rune & Berg Oy.

10.1.7 References

Työterveyslaitos, (2024). *TYÖOTE tukee työkykyä ja lisää tuottavuutta*. Available at: https://www.ttl.fi/teemat/tyoterveys/tyoterveyshuolto/tyoote-toimintamalli (accessed 20.9.2024).

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VTT Technology 431

Title	**E3 Pandemic Response** Final Report
Author(s)	Jaakko Paasi (Ed.)
Abstract	The document is the final report of E3 Excellence in Pandemic Response and Enterprise Solutions (E3) project. The project was launched in 2021 to address the need for resilient solutions to mitigate the impact of COVID-19 pandemic, and any new pandemics, on societies. The three-and-a-half-year project combines expertise from 7 Finnish research institutes and 22 companies, and with its 12 M€ total budget it was one of the largest co-innovation projects ever funded by Business Finland. The E3 Final Report is a compilation of full papers and extended abstracts from the main results of project work. It covers a broad range of topics in the multidisciplinary E3 project from medicine and microbiology, through aerosol physics and aerosol technology to building services engineering, and to behavioural and business sciences. In addition to research done in laboratories, interventions were done in hospitals and daycare centres to test the impact of countermeasures in mitigating the spread of pathogens. The most important single finding of the project was the result that, in daycare centres, children's morbidity decreased by 18 percent when the air was cleaned with air purifiers. The significant 18 percent reduction was achieved without implementing other infection mitigation strategies beyond air purification. The finding was a result of unique combination of clinical and technical research, enabled by the multidisciplinary approach of E3 project.
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Nimeke	**E3 Pandemic Response** Loppuraportti
Tekijä(t)	Jaakko Paasi (toim.)
Tiivistelmä	Tämä dokumentti on E3 Excellence in Pandemic Response and Enterprise Solutions (E3) -projektin loppuraportti. E3-projekti käynnistyi vuonna 2021 vastauksena COVID-19 pandemian mukanaan tuomaan tarpeeseen saada ratkaisuja, jotka kasvattavat yhteiskunnan resilienssiä vähentämällä taudinaiheuttajia ihmisissä ja heidän elinympäristöissään. Monitieteellinen E3-projekti yhdisti kaikkiaan 7 kotimaista tutkimuslaitosta ja 22 yritystä 3,5-vuotiseen hankkeeseen. Kokonaisbudjetiltaan 12 M€ suuruinen hanke oli yksi suurimmista Business Finlandin koskaan rahoittamista co-innovation-hankkeista. E3 Pandemic Response – loppuraportti on kokoomateos. Se käsittää sekä pidennettyjä tiivistelmiä että laajempia kuvauksia hankkeen keskeisistä tuloksista. Raportti tuo esiin monialaisen tutkimuksen tuloksia painottuen mm. lääketieteen, mikrobiologian, aerosolifysiikan ja -teknologian, talotekniikan ja käyttäytymis- ja liiketaloustieteen näkökulmiin. E3-hankkeen tärkeä piirre ja itse asiassa tulos on ollut kaikkien näiden osa-alueiden yhdistäminen konkreettisesti yhtenäiseksi tutkimukseksi. Yhteistutkimuksen tuloksia on pilotoitu ja viety määrätietoisesti käytäntöön erityisesti sairaala- ja päiväkotiympäristöissä tehdyissä interventiossa. Hankkeen tärkein yksittäinen tutkimustulos tulee Helsingin kaupungin päiväkodeissa tehdystä interventioista, jossa lasten sairastavuus aleni 18 % kun päiväkodin sisäilmaa puhdistettiin ilmanpuhdistimilla. Tämä 18 % sairastavuuden merkittävä alenema saavutettiin ilman, että muita tartuntojen lieventämisstrategioita toteutettiin ilman puhdistamisen lisäksi. Tutkimuksen taustalla oli kliinisen sekä tekniikan tutkimuksen lähestymistapojen ainutlaatuinen yhdistäminen, minkä E3-projektin monitieteellinen lähestymistapa mahdollisti.
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E3 Pandemic Response

Final Report

E3 Excellence in Pandemic Response and Enterprise Solutions project was a response to the need for resilient solutions to mitigate the impact of COVID-19 pandemic (and any new pandemics) on societies. This document presents the main results of the project.

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