CHALMERS
UNIVERSITY OF TECHNOLOGY

Air quality in care facilities

Reduction of possibly infectious particles to reduce the risk of infection

Master's thesis in the Master's Programme Sustainable Energy Systems

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Cover: The waiting room for the children's emergency room at Karolinska Universitetssjukhuset with the measurement station.
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ABSTRACT

This study investigates the effectiveness of air cleaning in reducing airborne particle and bacterial concentrations in healthcare environments, with the aim of lowering infection risk without increasing mechanical ventilation rates. The research combines laboratory experiments, infection risk modelling, and field measurements conducted in a hospital waiting room.

In laboratory conditions, the Clean Air Delivery Rate (CADR) of the electrostatic air cleaner was determined by using particle concentration decay measurements, resulting in an average value of approximately 400 l/s depending on particle size. These results were used to estimate equivalent air change rates and to model infection risk using the Wells–Riley approach via the REHVA calculator. The modelling indicates that the addition of a single air cleaner, with CADR capacity of 400 l/s, can reduce the theoretical probability of airborne infection by approximately 75-80 % compared to a baseline ventilation rate of 5 air changes per hour (ACH), outperforming an increase to 8 ACH.

Field measurements in a waiting room at Karolinska Universitetssjukhuset confirmed that air cleaning providing a substantial CADR significantly reduces airborne particle concentrations (up to 60–70%) and reduced bacterial levels (approximately 40–55%) under real operating conditions. However, bacterial reductions showed higher variability due to occupancy and activity levels. The results also demonstrate that air cleaners provide substantial improvements in indoor air quality at relatively low energy consumption, with an estimated annual energy use significantly lower than that required to achieve equivalent ventilation rates.

Measured ozone levels, a potential by-product of electrostatic air cleaning, used during the experiments, remained well below recommended limits, indicating safe operation, while noise levels increased moderately but remained within acceptable ranges for healthcare environments.

Overall, the findings demonstrate that electrostatic air cleaning can serve as an effective and energy-efficient supplementary strategy to ventilation for reducing airborne contaminants and infection risk in healthcare facilities, particularly in spaces with high occupancy or limited ventilation capacity.

Key words: Ventilation, airborne transmission, air changes, infection risk, air quality, air cleaners, healthcare guidelines, energy use, REHVA calculator tool, Wells-Riley equation, Karolinska Universitetssjukhuset

Luftkvalitet i vårdrum
Möjligt smittbärande partiklar

Examensarbete inom masterprogrammet Hållbara Energisystem

REBECKA STRÖM

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SAMMANFATTNING

Denna studie undersöker effektiviteten hos luftrening för att reducera luftburna partikel- och bakteriekoncentrationer i vårdmiljöer, med syftet att minska infektionsrisken utan att öka den mekaniska ventilationen. Studien kombinerar laboratorieexperiment, modellering av infektionsrisk samt fältmätningar utförda i ett väntrum på ett sjukhus.

Under laboratorieförhållanden bestämdes luftrenarens Clean Air Delivery Rate (CADR) genom mätningar av avklingning av partikelkoncentration, vilket resulterade i ett genomsnittligt värde på cirka 400 l/s beroende på partikelstorlek. Dessa resultat användes för att uppskatta motsvarande luftomsättningshastigheter samt för att modellera infektionsrisk med hjälp av Wells–Riley-modellen via REHVA:s beräkningsverktyg. Modelleringen visar att installation av en luftrenare med CADR kapaciteten 400 l/s, kan minska den teoretiska sannolikheten för luftburen infektion med cirka 75-80 % jämfört med en grundventilation på 5 luftomsättningar per timme (ACH), vilket överträffar effekten av att öka ventilationen till 8 ACH.

Fältmätningar i ett väntrum på Karolinska Universitetssjukhuset bekräftade att luftrening som ger en betydande CADR avsevärt minskar luftburna partikelkoncentrationer (upp till 60–70%) samt reducerar bakterienivåer (cirka 40–55%) under verkliga driftsförhållanden. Variationer i bakteriereduktion observerades dock till följd av skillnader i personbelastning och aktivitetsnivå. Resultaten visar även att luftrenare kan ge betydande förbättringar av inomhusluftens kvalitet vid relativt låg energianvändning, där den uppskattade årliga energiförbrukningen är avsevärt lägre än den som krävs för att uppnå motsvarande förbättring genom ökad ventilation.

Uppmätta ozonhalter, en potentiell biprodukt av elektrostatisk luftrening som används under experimenten, låg långt under rekommenderade gränsvärden, vilket indikerar säker drift, medan ljudnivåerna ökade måttligt men förblev inom acceptabla nivåer för vårdmiljöer.

Sammanfattningsvis visar resultaten att elektrostatisk luftrening kan utgöra en effektiv och energieffektiv kompletterande åtgärd till ventilation för att minska luftburna föroreningar och infektionsrisk i vårdlokaler, särskilt i utrymmen med hög personbelastning eller begränsad ventilationskapacitet.

Nyckelord: Ventilation, luftburen smittspridning, omsättningar, infektionsrisk, luftkvalitet, luftrenare, vårddirektiv, energianvändning, REHVA kalkylator, Wells-Riley ekvationen, Karolinska Universitetssjukhuset

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Preface

This master's thesis project was conducted between January and June 2026 at the Division of Building Services Engineering at Chalmers University of Technology, in collaboration with Karolinska Institutet and CIT Renergy. The work relates to the research project *New system solutions for infection control in response to demands for increased ventilation in healthcare facilities*, funded by Formas, a Swedish government research council focused on sustainable development (grant no. 2025-01294).

I would like to express my sincere appreciation to my supervisors, Lars Ekberg, at Chalmers University and Daniel Olsson, at CIT Renergy. They have been extremely supportive throughout this thesis and provided me with insightful advice and encouragement. I am also grateful for Johan Nordenadler at Karolinska Institutet and Isak Afram at Coor for being very helpful during the field study. Lastly I want to thank the staff at the emergency room for children at Karolinska Universitetssjukhuset for letting me conduct the field study there.

Gothenburg, June 2026
Rebecka Ström

Notations

Symbols and Units

ACH	Air Changes per Hour
°C	Celsius
cc	cubic centimeter
CO_2	Carbon Dioxide
k	Decay Rate Constant
L	Litre
m	Meter
nm	nanometer
μm	micrometer
μg	microgram
ppm	parts per million

Abbreviations

AC	Air Cleaner
BOV	Byggnation och Vårdhygien (Construction and Healthcare Hygiene)
CADR	Clean Air Delivery Rate
CFU	Colony Forming Units
FP	Fine Particles (sizes between 0.3 and 0.5 μm)
PTS	Program för Teknisk Standard (The Swedish Program for Technical Standards)
REHVA	Federation of European Heating, Ventilation and Air Conditioning Associations
SFVH	Svensk Förening för Vårdhygien (The Swedish Association for Healthcare Hygiene)
UFP	Ultra Fine Particles (<100nm); in this study defined based on P-Trak measurements (20 nm–1 μm)
WHO	World Health Organization

1 Introduction

Healthcare-associated infections remain one of the most significant challenges in modern healthcare systems. They are among the most common complications arising during medical care and treatment, leading to increased patient suffering, prolonged hospital stays, higher mortality rates, and substantial economic costs for healthcare providers and society. Preventing the spread of infections is therefore a critical priority in the design and operation of healthcare environments (Swedish Society for Healthcare Hygiene, 2025; University of Gothenburg, 2021). The physical design of healthcare facilities plays a central role in infection control. Well-designed buildings enable healthcare personnel to follow hygiene protocols effectively and reduce the risk of pathogen transmission. Achieving this requires not only knowledge of healthcare practices and infection control, but also expertise in building design, ventilation systems, and technical installations. Consequently, the development of hygienic healthcare environments require collaboration between medical professionals, infection control specialists, and engineers (Swedish Society for Healthcare Hygiene, 2025).

Airborne transmission of infectious diseases has gained increasing attention in recent years, particularly following the COVID-19 pandemic. It is now widely recognized that aerosols, small particles that can remain suspended in air for extended periods, are a major pathway for the spread of respiratory infections. This has led to a growing focus on indoor air quality (IAQ) and the role of ventilation systems in reducing infection risk. Increasing ventilation rates can dilute airborne contaminants; however, this approach is often associated with higher energy consumption, increased noise levels, and practical limitations in existing buildings. These challenges highlight the need for complementary solutions that can improve air quality without requiring major modifications to ventilation systems. One such solution is the use of portable or integrated air cleaning technologies. Electrostatic air cleaners, in particular, offer the potential to remove airborne particles efficiently while maintaining low pressure drop and energy consumption. By increasing the equivalent air change rate in a space, these devices may reduce infection risk in a cost-effective and energy-efficient manner.

Despite promising results from previous studies, there is still limited field-based evidence on the performance of electrostatic air cleaning in real healthcare environments, especially in Sweden. This thesis therefore investigates whether electrostatic air cleaners can effectively reduce airborne particle and bacterial concentrations in hospital settings and contribute to improved infection control without increasing ventilation airflow.

1.1 Objective

The overall objective of this thesis is to evaluate whether electrostatic air cleaning can reduce airborne particle and bacterial concentrations in hospital environments in Sweden, and thereby contribute to a lower risk of infection without increasing the mechanical ventilation rate. To achieve this, the study combines laboratory experiments, infection risk modelling, and field measurements. The performance of electrostatic air cleaners is assessed in terms of air quality improvement, energy use, and practical applicability in healthcare settings.

More specifically, the study aims to:

- Quantify improvements in indoor air quality (IAQ) through measurements of particle and bacterial concentrations.
- Determine the Clean Air Delivery Rate (CADR) and corresponding equivalent air change rate provided by the air cleaner.
- Evaluate the impact of air cleaning on infection risk using established modelling approaches.
- Assess energy consumption associated with air cleaning compared to increased ventilation.
- Investigate additional factors such as noise levels and ozone generation

An additional objective is to assess whether electrostatic air cleaning can serve as a permanent or supplementary solution in healthcare ventilation systems, either as standalone units in individual rooms or integrated into central ventilation systems.

Research questions

1. **Air quality performance:** To what extent can electrostatic air cleaning reduce airborne particle and bacterial concentrations?
2. **Infection risk:** How does the use of air cleaners affect the probability of airborne infection compared to increased ventilation?
3. **Energy performance:** Can equivalent air quality improvements be achieved with lower energy use compared to higher ventilation rates?
4. **Operational feasibility:** Are noise levels and ozone concentrations within acceptable limits for healthcare environments?
5. **Implementation potential:** Can electrostatic air cleaning be applied as a permanent solution in healthcare facilities?

2 Theory

This chapter presents the theoretical framework used to analyse airborne infection risk and evaluate the performance of air-cleaning technologies in healthcare environments. The chapter integrates concepts from infection transmission, ventilation theory, air-cleaning technologies, and quantitative risk modelling.

First, ventilation requirements for healthcare waiting rooms are reviewed to establish the regulatory and operational context for indoor air quality and infection control. The concept of Clean Air Delivery Rate (CADR) is then introduced and related to the equivalent air change rate as a metric for assessing the performance of portable air cleaners. Laboratory experiments were conducted to determine the CADR of the electrostatic air cleaner used in this study.

The experimentally derived CADR values are subsequently applied in infection risk modelling using the REHVA calculator, enabling a comparison between air-cleaning strategies and increased ventilation rates. Finally, the theoretical framework and modelling results are used to formulate the research hypothesis tested in the field study.

2.1 Airborne infection and transmission

Viruses consist of genetic material (DNA or RNA) enclosed within a protein structure. Many respiratory viruses, such as influenza, are RNA viruses, which are generally more prone to mutation. Viruses cannot replicate independently and must infect host cells to reproduce, often destroying the host cell and releasing large quantities of new viral particles. Infected individuals are typically most contagious around the onset of symptoms; however, transmission can also occur from asymptomatic individuals. Viral transmission occurs through several pathways. The dominant route is via respiratory droplets expelled during coughing, sneezing, speaking, or breathing. These droplets vary in size and behaviour. Airborne transmission occurs through inhalation of aerosols, small particles that can remain suspended in the air for extended periods. The risk of airborne infection increases in poorly ventilated spaces and with prolonged exposure. The probability of infection via inhalation depends on several factors, including the airborne virus concentration, breathing rate, deposition fraction in the respiratory tract, and exposure duration. Larger respiratory droplets typically travel short distances (approximately 1–2 m) before depositing on mucous membranes of susceptible individuals. In addition, indirect transmission may occur via fomites, where contaminated surfaces are touched and subsequently transferred to the face. Depending on environmental conditions, viruses can remain viable on surfaces for hours to days (Public Health Agency of Sweden, 2023; University of Gothenburg, 2021).

Particle size plays an important role in transmission dynamics. Virus-laden aerosols are typically in the range of 20–200 nm, whereas bacteria are often associated with larger particles in the range of 0.2–5 μm. Larger droplets settle rapidly, while smaller droplets can evaporate into droplet nuclei and remain airborne. Bacteria generally exhibit slower decay indoors compared to viruses, partly due to differences in sensitivity to environmental factors such as humidity (Azimi & Stephens, 2013; Kowalski & Bahnfleth, 1998).

2.2 Ventilation

Increasing ventilation airflow is one of the primary strategies for reducing airborne infection risk in indoor environments. By introducing pathogen-free outdoor air, ventilation dilutes the concentration of airborne contaminants and thereby lowers the probability of transmission. However, the relationship between airflow rate and infection risk is non-linear and must be balanced against energy use, spatial constraints, and indoor environmental quality. At low ventilation rates, increasing airflow results in a substantial reduction in infection risk. For example, increasing ventilation from 2 to 4 air changes per hour (ACH) can significantly decrease airborne contaminant concentrations. However, further increases yield diminishing returns, as each additional unit of airflow contributes progressively less to risk reduction (Filipsson & Ekberg, 2024). The effectiveness of ventilation also depends strongly on the source strength, i.e., the infectiousness of the emitter and the rate of particle generation. While higher airflow rates consistently reduce relative risk, the absolute reduction in transmission may be limited in cases where the source strength is low. Increasing airflow rates is associated with several practical limitations. Higher ventilation rates lead to increased energy demand for heating, cooling, and fan operation. The performance of heat recovery systems is therefore a critical factor in mitigating energy penalties. In addition, high airflow rates may negatively affect indoor environmental quality by causing thermal discomfort due to drafts, elevated noise levels, and reduced indoor humidity. Lower relative humidity may in turn influence virus survival and occupant susceptibility. From a design perspective, increased airflow also imposes spatial constraints. Higher flow rates require larger duct systems and air handling units to maintain acceptable air velocities and acoustic conditions, which can reduce usable floor area and complicate building design (Filipsson & Ekberg, 2024). These limitations highlight the need for complementary strategies that can reduce airborne infection risk without proportionally increasing ventilation airflow.

2.2.1 Ventilation strategies in healthcare

Ventilation systems in healthcare facilities are designed to fulfil multiple objectives, including infection control, thermal comfort, pressure control, and compliance with regulatory requirements. Unlike most other building types, healthcare environments must account for varying patient vulnerability, diverse infection risks, and strict hygienic standards. Consequently, ventilation design is closely linked to the function of each space, such as patient rooms, operating theatres, isolation rooms, and waiting areas. Most healthcare facilities rely on mechanical ventilation systems that provide a predefined airflow rate, typically expressed as air changes per hour (ACH) or airflow per occupant. A common strategy is turbulent mixing ventilation, where supply and extract airflows are arranged to promote a well-mixed indoor environment and dilute airborne contaminants. In contrast, operating theatres and cleanrooms often use unidirectional airflow (UAF), often used to achieve ultra-clean air (UCA). These systems deliver a uniform flow of highly filtered air over critical zones, such as the surgical site, to minimize contamination. This approach requires significantly higher airflow rates compared to mixing ventilation (Friedericy et al., 2024).
Pressure-controlled ventilation is also widely used in healthcare settings. Negative pressure is applied in isolation rooms to prevent the spread of airborne pathogens to adjacent areas, while positive pressure is used in operating theatres and protective

environments to prevent ingress of contaminated air.

In practice, ventilation systems in healthcare buildings are often designed for worst-case conditions and operate at constant or near-constant airflow rates. While this ensures compliance with guidelines, it introduces several limitations. Increasing ventilation rates beyond design values is frequently constrained by energy consumption, noise, duct capacity, and the limitations of existing infrastructure. These constraints are particularly significant in older healthcare buildings, where system upgrades may be technically complex or economically unfeasible. Furthermore, ventilation alone may be insufficient in spaces with high and variable occupancy, such as waiting rooms. Frequent door opening, occupant movement, and air exchange with adjacent spaces can reduce ventilation effectiveness and lead to non-uniform air distribution. In such environments, achieving adequate dilution of airborne contaminants solely through increased ventilation is challenging. These limitations highlight the potential role of supplementary air-cleaning technologies, which can increase the equivalent air change rate without requiring major modifications to existing ventilation systems.

2.2.2 Ventilation requirements in healthcare facilities

Ventilation requirements in healthcare environments are defined by both infection control guidelines and building standards, which may lead to differing recommendations. The Swedish Association for Infection Control recommends a ventilation rate of approximately 8 ACH for waiting rooms associated with emergency departments (Swedish Society for Healthcare Hygiene, 2025).

In contrast, the Swedish Program for Technical Standard (PTS) specifies ventilation rates based on floor area and occupancy, given as 1 l/(s·m^2) plus 7 l/(s·person) (Region Jonkoping County, 2023d). For a reference waiting room with an area of 25m^2 and an occupancy of ten persons, this corresponds to approximately 5 ACH.

Increasing the ventilation rate from 5 to 8 ACH therefore represents a substantial increase in airflow and associated energy demand. This raises the question of whether similar reductions in airborne infection risk can be achieved through alternative strategies. One potential approach is the use of portable air-cleaning technologies, which remove airborne particles and thereby increase the equivalent air change rate. Such systems may offer a practical means of improving indoor air quality and reducing infection risk without requiring significant modifications to existing ventilation systems.

2.3 Factors influencing airborne infection risk

Several established measures exist to reduce the risk of infection. The most efficient measure is elimination and distancing, this means removing the infectious person and distancing to reduce direct exposure. Ventilation and increasing air exchange rates or air cleaners reduce the concentration of viral particles in the air. There are also administrative controls that can be put in place to reduce the risk of infection, this includes hygiene protocols, cleaning schedules and organizational changes to reduce occupant density. Another effective measure is personal protective equipment, which includes surgical masks and respirators (University of Gothenburg, 2021).

2.3.1 Humidity

Relative humidity is concluded to have an impact on the risk of infection, too low humidity, 20%, and too high humidity, 70% both increase the risk of infection. This is due to the biological decay of the virus, that loses infectivity over time, which is highly affected by the humidity (Aganovic et al., 2023). Low relative humidity increases the risk of infection because dry air irritates mucous membranes in the nose, throat and eyes. In dry conditions particles may linger in the air longer and settle slower (Filipsson & Ekberg, 2024). Most respiratory viruses exhibit seasonal variations, peaking in the winter months due to factors like lower humidity, human behaviour like indoor crowding and reduced immune response due to cold and dry air (Public Health Agency of Sweden, 2023; University of Gothenburg, 2021). High humidity leading to condensation can promote mould growth, which also constitutes a health hazard (World Health Organization, 2009).

2.3.2 Masks / UVGI / filtration

Aganovic et. al (Aganovic et al., 2023) studied the difference between different removal mechanisms on the airborne infection risk of SARS-CoV-2 variants. There are four mechanisms studied which are: ventilation rate, filtration efficiency in case of recirculated air, face masks and upper room UVGI radiation. From this study it is concluded that it is possible to reduce the risk of infection below 10% with either ventilation, face masks or UVGI. In this case the baseline risk of infection was 23%. The risk of infection can be reduced even further if the exposure time is shorter in all of the cases.

2.3.3 Clothing

Surgical clothing plays a significant role in controlling airborne contamination and reducing postoperative infection rates. The widespread use of worn cotton surgical garments in many low-income healthcare settings contributes to increased bacterial dispersion compared to single-use synthetic clothing. Cotton materials tend to release more particles and microorganisms into the air, thereby elevating the risk of surgical site infections. Studies have shown that switching from cotton garments to single-use synthetic clothing can substantially reduce airborne bacterial counts. Additional improvements, such as sealing gaps around the feet, further limit the spread of microorganisms. The most effective reductions in airborne bacteria were observed when improved surgical attire was combined with other infection-control measures, highlighting clothing as a critical component of a comprehensive strategy to reduce infection risk (Rutegård et al., 2025).

2.4 Air cleaning

Air cleaning through mechanical filtration is a widely applied strategy for controlling airborne particles and viable microorganisms in healthcare environments.

2.4.1 HEPA and fiber filtration

High-Efficiency Particulate Air (HEPA) filters are capable of removing at least 99.95% of particles at a diameter of 0.3 μm and are commonly used in cleanrooms, pharmaceutical production, isolation units, and operating theatres where aseptic

conditions are required. Their high efficiency is achieved through dense fibrous media that capture particles via interception, inertial impaction, and diffusion. While HEPA filtration provides the highest level of particle removal, it is associated with a relatively high pressure drop, which increases fan energy consumption and operational costs. In many hospital ventilation systems, medium- or high-efficiency fiber filters (e.g., 90–95% filters) are instead used as a compromise between particle removal and energy performance. These filters can significantly reduce concentrations of spores and bacteria and, in some cases, maintain indoor particle levels below outdoor ambient levels. However, their removal efficiency for smaller particles, including virus-laden aerosols, is lower than that of HEPA filters. In conventional HVAC systems, pathogen reduction is therefore often achieved through a combination of outdoor air ventilation and mechanical filtration rather than filtration alone (Kowalski & Bahnfleth, 1998; Romano et al., 2020).

The use of dense fibrous filter media inherently creates a trade-off between filtration efficiency and pressure drop. Higher efficiency typically requires finer fibers and increased media density, which results in greater airflow resistance and higher energy demand. This trade-off has motivated the development of alternative air-cleaning technologies that aim to maintain high removal efficiency while minimizing pressure losses.

2.4.2 Electrostatic air cleaning

Electrostatic air cleaning uses a filtration module equipped with a fan that draws air into the system, where particles are electrically charged using a high-voltage circuit. The air then passes through a lamella-structured filter where every other lamella is grounded and every other has electrical potential, causing the particles to adhere to the filter surfaces. This mechanism enables high particle separation efficiency while maintaining very low airflow resistance. As a result, electrostatic air cleaners are space-efficient, quiet, and energy-efficient. Future developments aim to evaluate whether such filters can be implemented as permanent installations for rapid air cleaning (Rutegård et al., 2025). More broadly, electrostatic air cleaning is designed to address the trade-off between high filtration efficiency and low pressure drop in ventilation systems. Unlike conventional mechanical filters, which rely on dense fiber structures to capture fine particles, often leading to increased air resistance and energy consumption, electrostatic filters use electric forces to remove particulate matter and, in some cases, gaseous pollutants more efficiently when electrostatic filters are assisted with coats containing activated carbon, manganese dioxide, zinc oxide, copper oxide and barium titanate (Tian et al., 2020).

A previous study conducted in March 2024 at Kungälv hospital evaluates the efficiency of prototype electrostatic air cleaners in healthcare environments designed for quiet operation and high capacity (Olsson & Ekberg, 2024). The investigation focused on quantifying the reduction of airborne particles and bacteria in both waiting rooms and a newly built patient room to assess infection risk mitigation. To determine the clean airflow rates, pollutants (lime powder), were introduced to the rooms. A particle counter measured the dilution of particle concentration over time, comparing decay rates with the air cleaner switched on versus off. Active microbial samplers collected air samples on nutrient plates, bacterial colonies (CFU), were cultured and counted to measure the biological load in the air. The waiting room had a large volume

with significant air mixing from corridors, while the patient room was smaller, closed off and tested under three different ventilation flow rates. The results from this study indicates a significant improvement in air quality when the cleaner was active. Particularly in the enclosed patient room, where the air cleaner drastically reduced bacteria content, regardless of the baseline ventilation flow, bacteria levels dropped to approximately one tenth of the baseline value. Due to the larger volume of the waiting room and the open connections to corridors, the relative impact was lower, but still positive. The study confirms that supplementary air cleaning units can substantially lower airborne contaminants. The results highlight that while ventilation aids in dilution, the addition of high capacity air cleaners provides a massive boost to the equivalent air change rate, significantly lowering the theoretical risk of spreading airborne infections in hospital settings (Olsson & Ekberg, 2024).

Previous studies illustrate the critical role of air cleaning systems in reducing postoperative infections, particularly in low-resource healthcare settings where access to advanced ventilation is often limited. Airborne contamination is a significant driver of surgical site infections, a risk that is markedly higher in low-income countries compared to high-income nations (Rutegård et al., 2025). In many low-income regions, operating rooms often lack mechanical ventilation or rely on basic air conditioners that cool air without cleaning it. This leads to microorganism concentrations that are significantly higher than international standards. Additionally, the widespread use of worn cotton surgical clothing contributes to higher bacterial dispersion compared to single-use synthetic garments. The prototype cost-effective electrostatic air cleaners have been developed to address these challenges. The system works by creating positive pressure, preventing untreated air from entering the room, and recirculating room air through the filter. The technology charges particles electrically, allowing them to be trapped in the collection filter without generating ozone. This method is noted for low energy consumption, minimal noise and ease of maintenance. Field tests conducted in simulated and real surgical environments demonstrated that installing these simple electrostatic air cleaners drastically reduced airborne particles and bacteria. In one case study involving a permanent installation, bacterial levels dropped significantly when the cleaners were active. The study highlighted that while air cleaning is effective, the type of surgical clothing also plays a vital role. Switching from cotton to single-use clothing, and sealing gaps around the feet, led to further substantial reductions in airborne bacteria. The most optimal results were achieved through a combination of effective air cleaning and improved surgical attire. In tests, the combination of cleaners and protective clothing reduced bacterial counts to approximately 1% of the original levels. Even with suboptimal conditions-such as dirty surfaces and lower voltage power supplies, the air cleaning system successfully brought bacterial levels down to ranges comparable with standard hygiene guidelines for general surgery (below 100 CFU/m^3) (Rutegård et al., 2025).

2.4.3 Summary and research gap

Despite extensive research on ventilation and protective measures, there is limited field-based evidence on the effectiveness of electrostatic air cleaning as a supplementary or permanent solution in Swedish healthcare environments. Mechanical ventilation and HEPA filtration are well established as means of reducing airborne contaminants in healthcare settings, and electrostatic air cleaning has shown strong

results in operating theatres and in a single Swedish hospital study (Olsson & Ekberg, 2024). Field evidence in other healthcare environments, particularly emergency waiting rooms, which combine high occupancy turnover, frequent door opening, and vulnerable patients, is still scarce. There is also limited published work directly comparing the infection risk reduction achievable through air cleaning with the reduction achievable through an equivalent uplift in mechanical ventilation. This thesis addresses both gaps by combining laboratory CADR measurements, Wells–Riley-based modelling, and an eight-day field study in a children's emergency waiting room.

2.5 Guidelines

Guidelines provide boundary conditions and performance targets against which the proposed technology is evaluated. The World Health Organization, WHO, has published a guideline regarding natural ventilation in healthcare settings in 2009 (World Health Organization, 2009). It is concluded that adequate ventilation dilutes airborne pathogens, reducing the risk of infection and the probability of infection can be modeled using the Wells-Riley equation. WHO also published specific guidelines regarding indoor ventilation in the context of COVID 19 in 2021 (World Health Organization, 2021). These guidelines are based on the natural ventilation guidelines and are applied for building with mechanical ventilation. The minimum ventilation rate is 160 l/s/patient or 12 ACH for areas with aerosol generating procedures, and 60 l/s/patient otherwise. These recommendations are based on the report from 2009, which is based on data from several different reports. One of them is a study from Canada regarding ventilation and the risk of tuberculosis infection in healthcare workers (Menzies et al., 2000). The results of this report concluded that tuberculosis infection was associated with ventilation in rooms with less than 2 ACH.

The Swedish association for infection control stated in a report published 2025-06-24 that they recommend a total airflow of 40 to 60 l/s/patient, where the lower end represents patients with low risk of airborne infections, and the higher flow represents sensitive patients with higher risk of infection (Swedish Society for Healthcare Hygiene, 2025). Table 2.1 shows the different guidelines for some of the different types of care rooms. The Swedish program for technical standard, PTS, states different values for different rooms. In Table 2.2 the different air flow rates are shown and recalculated based on the data for each individual room to show the values in ACH (Region Jonkoping County, 2023a, 2023b, 2023c, 2023d). As seen in Table 2.1 and 2.2, there is a difference in guidelines for the ventilation rate depending on if the recommendation comes from the care side or the building side.

Table 2.1: Guidelines from the Swedish association for infection control (Swedish Society for Healthcare Hygiene, 2025)

Room	ACH	Total airflow [l/s per patient]
Waiting room (ER)	8	-
Reception room	2 - 4	20 - 60
Care room	3 - 4	30 - 60
Care room intensive care	6	40
Emergency / Trauma room	8	40
Isolation room	8	120
Protective isolation	4 - 8	60 - 120

Table 2.2: Guidelines from the Swedish program for technical standard (Region Jonkoping County, 2023a, 2023b, 2023c, 2023d)

Room	Total airflow	Recalculated to ACH
Waiting room	1 l/s/m^2 + 7 l/s/person	5.07
Care room 1 patient	25 l/s	1.85
Examination room	2.5 l/s/m^2	3.33
Treatment room	2.5 l/s/m^2	3.33

2.6 Equivalent air change rate and CADR

The performance of portable air cleaners is commonly quantified using the Clean Air Delivery Rate (CADR). CADR represents the effective volumetric flow rate of particle-free air delivered by an air-cleaning device and can therefore be interpreted as an additional equivalent ventilation rate. In this way, CADR allows direct comparison between air cleaning and mechanical ventilation in terms of their contribution to reducing airborne contaminant concentrations. In a well-mixed indoor environment, the total removal of airborne particles can be expressed as the sum of all removal mechanisms, including ventilation, deposition, and air cleaning. The contribution of an air cleaner can therefore be expressed as an equivalent increase in air changes per hour (ACH).

2.6.1 CADR calculation

CADR is determined experimentally by analysing the decay rate of airborne particle concentration in a controlled environment. The method is based on the assumption of exponential decay in a well-mixed room.

Two measurement phases are required:

- **Natural decay:** Particle concentration decay is measured without the air cleaner in operation. This reflects removal due to ventilation, deposition, and other passive mechanisms.
- **Active decay:** The measurement is repeated with the air cleaner operating, resulting in an increased decay rate due to additional particle removal.

The particle concentration $C(t)$ can be described by an exponential decay function:

$$C(t) = C_0 e^{-kt}, \tag{2.1}$$

where k is the decay constant (s^{-1} or h^{-1}), representing the effective air change rate. The contribution of the air cleaner is obtained by subtracting the natural decay rate from the total decay rate:

$$ACH_{\text{cleaner}} = k_{\text{on}} - k_{\text{off}} \tag{2.2}$$

The CADR is then calculated as:

$$CADR = ACH_{\text{cleaner}} \cdot V, \tag{2.3}$$

where V is the room volume.

2.7 Wells Riley model

A study investigating the efficiency and cost-effectiveness of HVAC filtration strategies for controlling the airborne transmission of infectious diseases, used influenza in an office environment as a case study. By comparing recirculating air filtration against outdoor air ventilation, the analysis provides a framework for understanding how building operations impact occupant health and energy consumption (Azimi & Stephens, 2013).

The Wells-Riley model is a mathematical framework used to assess the risk of airborne infection in indoor environments. The model is built on the concept of a "quantum of infection". This represents the rate at which infectious airborne particles (quanta) are generated. It is used to calculate the likelihood that an individual in a "steady-state well-mixed indoor environment" will be exposed to these particles and subsequently become infected. The classical model typically involves several key variables to determine the probability of infection:
p : The breathing rate of an individual$(m^3/hour)$.
q : The quanta generation rate$(1/hr)$.
t : The exposure time(hr).
I : Nr of infectors
Q_{oa} : The room ventilation rate with pathogen-free air$(m^3/hour)$ (Azimi & Stephens, 2013).

$$P_{infection} = 1 - e^{\frac{-Ipqt}{Q_{oa}}} \tag{2.4}$$

Recent research has expanded the classical model to account for more complex variables and "removal mechanisms" to improve accuracy. Modern models allow for variations in expiratory modes (e.g., breathing vs. speaking), virus variants, viral load, and the number of infected persons. The model can be expanded to include; ventilation and portable air cleaners, viral inactivation due to relative humidity, inactivation via UVGI (Ultraviolet Germicidal Irradiation) in recirculated air or upper-room systems and filtration from the use of face masks. Researchers have integrated "size-dependent loss terms" to account for how different aerosol droplet sizes behave and are filtered (e.g., ASHRAE Standard 52.2). While the original model assumes a "well-mixed"

environment, advanced versions address two specific limitations which are incomplete mixing and time-varying exposure. The introduction of "ventilation efficiency" and "zonal versions" of the model helps account for environments where air is not perfectly mixed. Some versions have been developed to handle exposures that change over time rather than remaining at a steady state (Azimi & Stephens, 2013), (Aganovic et al., 2023).

2.7.1 REHVA calculator

In this study, the REHVA calculator to estimate the effect of ventilation on COVID-19 airborne transmission (REHVA, 2022) will be used to estimate the probability of infection, which is based on the Wells Riley model. An acceptable probability of infection can be derived from the reproduction number R, which is the number of new cases divided by the number of infectors. In order is to prevent the disease from spreading effectively within the population, the basic reproduction number R_0 must be kept below 1. Consequently, calculators often optimize ventilation and occupancy to ensure the event reproduction number remains below this threshold.

3 Methods

This study is based on a combination of laboratory experiments and field measurements. Laboratory tests were conducted to determine the performance of the air cleaners under controlled conditions, while field measurements were carried out in a hospital waiting room to evaluate their effectiveness in a real environment. The results were further analysed in relation to infection risk using established modelling approaches.

3.1 Laboratory work

Laboratory experiments were conducted to quantify the performance of the electrostatic air cleaners under controlled conditions. The primary objective was to determine the Clean Air Delivery Rate (CADR), as well as to assess energy use and ozone generation.

The experiments were performed in a clean laboratory room with the mechanical ventilation system switched off in order to minimise external airflow influences. Particle concentrations were artificially increased using two different particle sources: powder similar to chalk and a smoke pen. These sources represent particles of different size ranges, allowing the performance of the air cleaner to be evaluated across a range of particle diameters.

3.1.1 Experimental environment

The experiments were performed in a controlled laboratory room with the mechanical ventilation system switched off in order to minimise external airflow and ensure that particle removal was dominated by the air cleaner and natural decay processes.

Indoor environmental conditions during the experiments were approximately:

- Temperature: $\approx 22°C$
- Relative humidity: $\approx 30\%$

3.1.2 Experimental procedure

To evaluate the particle removal efficiency, airborne particle concentrations were artificially increased using two different particle sources:

- Chalk powder (representing larger particles)
- Smoke pen (representing smaller particles)

This allowed assessment of air cleaner performance across different particle size ranges.

For each experiment, two phases were conducted:

1. **Natural decay (air cleaner off)** Particle concentration decay was measured without the air cleaner in operation. This represents removal due to deposition and any residual air exchange.
2. **Active decay (air cleaner on)** The experiment was repeated with the air cleaner operating, resulting in an increased decay rate due to active particle removal.

Particle concentration was recorded continuously during both phases.

3.1.3 CADR determination

The Clean Air Delivery Rate (CADR) was determined using the decay rate method described in Section 2.6. Particle concentration decay was assumed to follow an exponential function. The decay constants were obtained by curve fitting of the measured concentration data. The contribution of the air cleaner was calculated as the difference between the decay rate with and without the air cleaner:

$$ACH_{cleaner} = k_{on} - k_{off} \tag{3.1}$$

And the CADR is the calculated as

$$CADR = ACH_{cleaner} \cdot V, \tag{3.2}$$

where V is the room volume.

Multiple instruments were used to determine CADR for different particle size ranges, and an average value was later selected for use in infection risk modelling.

3.1.4 Measurement instruments

Three particle monitoring instruments from TSI were used during the experiments, as well as an ozone monitor and an air sampler for microbiological measurements:

- **DustTrak DRX 8533** – measures mass concentration of PM1, PM2.5 and PM10 (mg/m^3)
- **P-Trak model 8525** – measures ultrafine particle number concentration (20 nm - 1 μm) ($particles/cm^3$).
- **AeroTrak model 9303** – optical particle counter measuring particles $\leq$0.3, 0.5 and 1 μm (particles/l)
- **Dual Beam Ozone Monitor** - Model 205, 2B Tech
- **Klotz Impaktor FH6** - air sampler for control of microbiological air quality

Measurements were conducted using both one-minute and ten-second sampling intervals, air sampling for microbiological air quality were conducted for five minutes for each sample.

Note In this study, ultrafine particles (UFP) are defined based on measurements obtained from the P-Trak instrument, which detects particles in the size range 20 nm to 1 μm. Strictly speaking, UFP are commonly defined as particles with diameters below 100 nm. However, in typical indoor environments, particle number concentrations are dominated by particles in the ultrafine range (<100 nm), while contributions from larger particles are relatively negligible. Therefore, P-Trak measurements are considered a reasonable proxy for UFP number concentration. Throughout this report, the term UFP is used to refer to the particle fraction measured by the P-Trak instrument.

3.1.5 Ozone measurements

Ozone generation from the air cleaner was evaluated in a separate laboratory experiment. The air cleaner was operated continuously, and ozone concentration was

measured using a calibrated Dual Beam Ozone Monitor. The test conditions were designed according to standard test conditions Swedish standard SS-EN 60335-2-65 for air-cleaning devices, with controlled temperature and humidity.

3.1.6 Ionisation

The experiment was conducted for four cases in a clean room. The clean room is 24 m^3 with ventilation turned off. Particle concentrations were measured with AeroTrak (>0.3, >0.5, >1, >5 μm/L) and bacterial concentrations measured with Klotz Impaktor FH6. One person walked in circles around the measurement devices in the clean room to generate bacteria. Between tests, particle levels were allowed to return to the zero-level baseline; bacteria were sampled once particle levels had reached equilibrium. The four cases are:

- Zero level test
- Only ionisation
- Only air cleaning
- Ionisation and air cleaning

3.1.7 Energy measurements

The electrical power consumption of the air cleaner was measured during operation. These measurements were later used to compare the energy performance of air cleaning with increased ventilation.

3.1.8 Limitations

The laboratory experiments were conducted in a controlled environment with limited air exchange, which differs from real healthcare settings. As a result, the measured CADR values represent the intrinsic performance of the air cleaner under idealised conditions and may differ from performance in the field.

3.2 Field testing

Field measurements were conducted in a waiting room at the children's emergency department at Karolinska Universitetssjukhuset. The purpose of the field study was to evaluate the real-world performance of electrostatic air cleaners in reducing airborne particle and bacterial concentrations under normal operating conditions.

3.2.1 Experimental design

The study was carried out over eight measurement days. During this period, different configurations of air cleaners were tested by alternating between conditions where the air cleaners were switched on and off. This enabled comparison between baseline conditions and active air cleaning within the same environment. The experimental approach can be described as a controlled intervention study with alternating on/off conditions, where:

- Baseline condition: air cleaners switched off
- Intervention condition: air cleaners switched on

In some cases, different numbers and combinations of air cleaners were used, as well as different fan settings, to evaluate performance under varying operational conditions.

3.2.2 Measurement procedure

Measurements were conducted continuously during occupied hours, typically between morning and afternoon. Particle concentrations were recorded at a time resolution of one measurement per minute, allowing analysis of temporal variations. In parallel with particle measurements, contextual parameters were documented manually, including:

- Number of occupants (patients and staff)
- Door status (open/closed)
- Presence and operation of air cleaners
- Researcher presence in the room
- Interruptions in measurements (instrument downtime)

The number of occupants varied significantly throughout the day, and was recorded as intervals for each measurement period.

3.2.3 Measured parameters

The following indoor air quality parameters were measured:

- Ultrafine particle concentration (particles/cm^3)
- Particle number concentrations at 0.3 μm, 0.5 μm, and 5 μm (particles/l)
- Mass concentrations: PM1, PM2.5, PM10 ($\mu g/m^3$)
- Bacterial concentration (CFU/m^3)
- Carbon dioxide (CO_2) concentration (ppm)
- Temperature (°C)
- Relative humidity (%)

These parameters were selected to represent both particle exposure and indoor environmental conditions, as well as to enable comparison with infection risk modelling.

3.2.4 Measurement instruments

The same instruments as in the laboratory study were used:

- **DustTrak DRX 8533** – measures mass concentration of PM1, PM2.5 and PM10 (mg/m^3)
- **P-Trak model 8525** – measures ultrafine particle number concentration (20 nm - 1 μm) ($particles/cm^3$)
- **AeroTrak model 9303** – optical particle counter measuring particles $\leq$0.3, 0.5 and 1 μm (particles/l)
- **Klotz Impaktor FH6** - air sampler for control of microbiological air quality

3.2.5 Operational conditions and variability

The field study was conducted under real hospital conditions, meaning that several uncontrolled factors influenced the measurements:

- Variable occupancy levels
- Frequent door opening and air exchange with adjacent corridors
- Changes in ventilation operation (e.g. base ventilation vs demand-controlled ventilation)
- Variations in outdoor air quality and weather conditions
- Placement and settings of air cleaners

3.2.6 Data processing and analysis

To enable comparison between different conditions, the data were aggregated into time intervals corresponding to periods with consistent experimental conditions (e.g. air cleaner on/off). For each period, average values were calculated for:

- Particle concentrations
- PM fractions
- CO_2, temperature, and relative humidity
- CFU

The effect of air cleaners was evaluated by comparing mean concentrations between on and off conditions under similar occupancy levels.

4 Laboratory Results

The laboratory experiments were conducted to quantify the Clean Air Delivery Rate (CADR) of the electrostatic air cleaner under controlled conditions. The results provide the basis for estimating equivalent air change rates and are subsequently used in infection risk modelling and to formulate the field study hypothesis.

4.1 CADR

Figures 4.1, 4.2, 4.3, 4.4, 4.5 and 4.6 present the measured particle concentration decay curves for the different instruments and particle sources. The calculated CADR values based on the decay rates are summarised in Table 4.1.

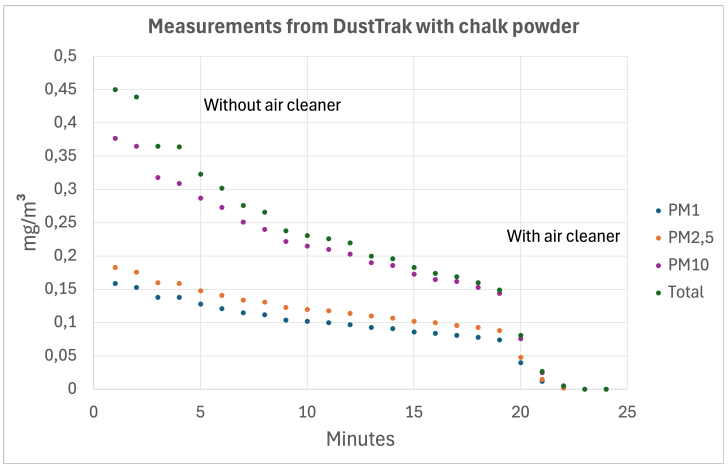


Figure 4.1: Measurements from Dust Trak with chalk powder

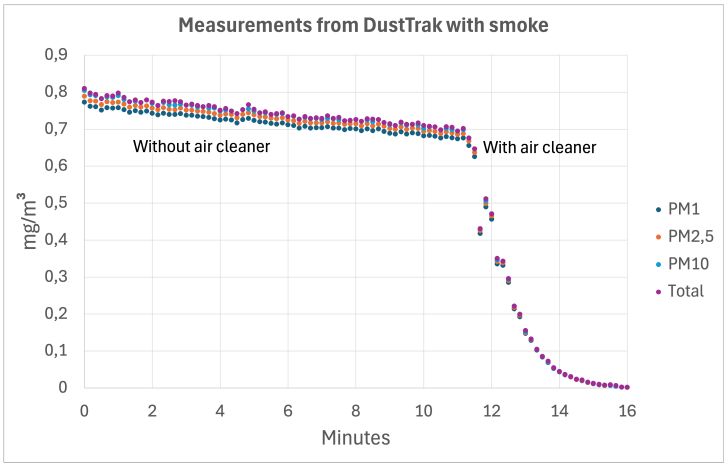


Figure 4.2: Measurements from Dust Trak with smoke

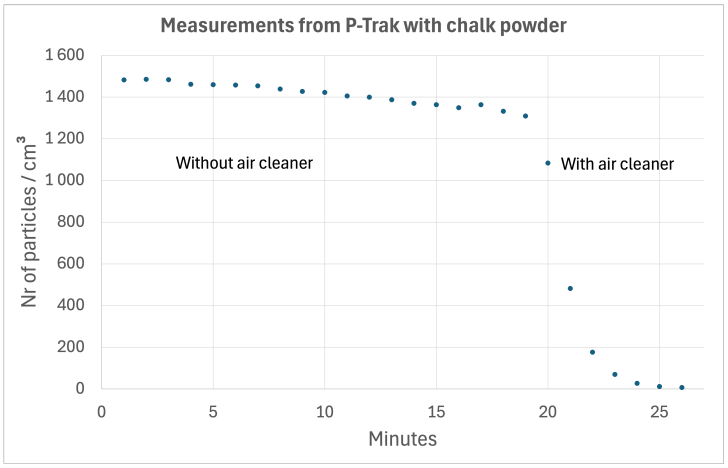


Figure 4.3: Measurements from P Trak with chalk powder

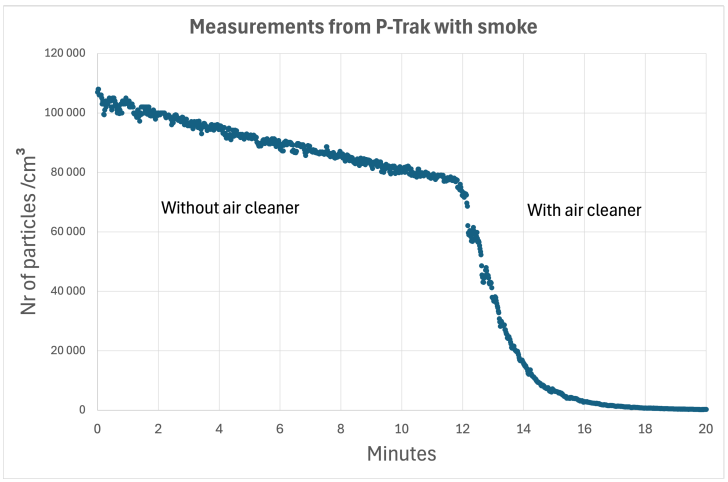


Figure 4.4: Measurements from P Trak with smoke

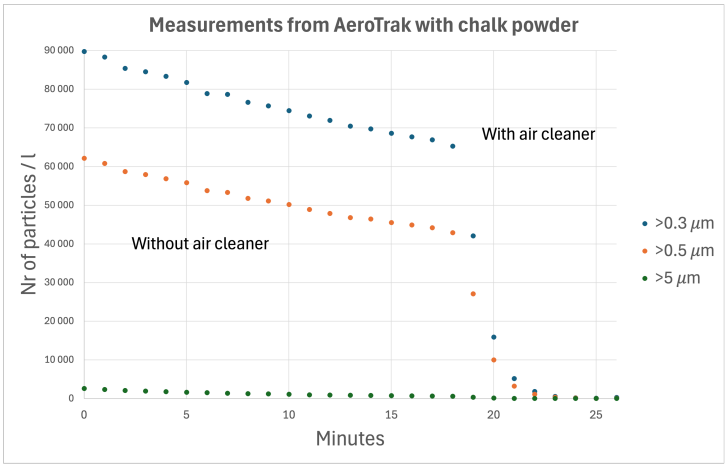


Figure 4.5: Measurements from Aero Trak with chalk powder

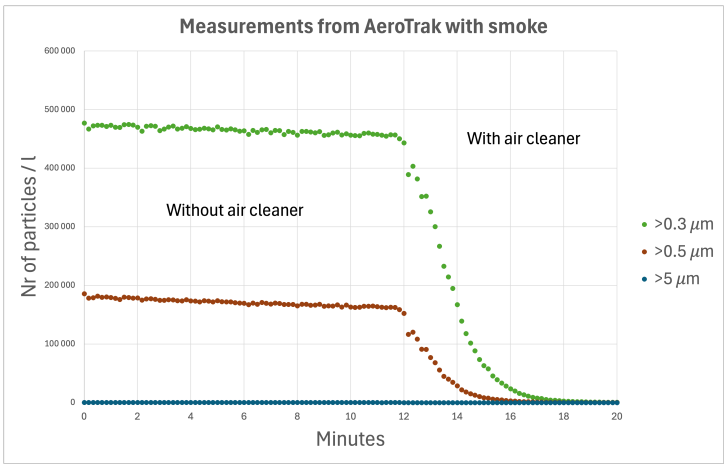


Figure 4.6: Measurements from Aero Trak with smoke

Table 4.1: CADR for the air cleaner, rounded to the nearest ten, reflecting the limited precision of the decay method.

	Chalk powder	Smoke
CADR Dust Trak [l/s]	480	480
CADR P Trak [l/s]	340	300
CADR Aero Trak [l/s]	410	400

The P-Trak measured lower CADR values compared to the other instruments. This is likely because it measures finer particles (>20 nm), which are generally more difficult to remove. The higher CADR values observed for larger particle sizes are consistent with the expected performance of electrostatic air cleaning systems, which typically remove larger particles more efficiently. The variation between instruments reflects particle size-dependent removal efficiency. Since bacteria and virus-laden aerosols are typically associated with particles larger than 0.5 μm, the mean CADR value of approximately 400 l/s was selected as a representative value for subsequent infection-risk modelling.

4.2 Infection risk modeling

The REHVA infection risk calculator (REHVA, 2022) was used to estimate the probability of infection and the event reproduction number under different ventilation and air-cleaning scenarios. The following scenarios were analysed:

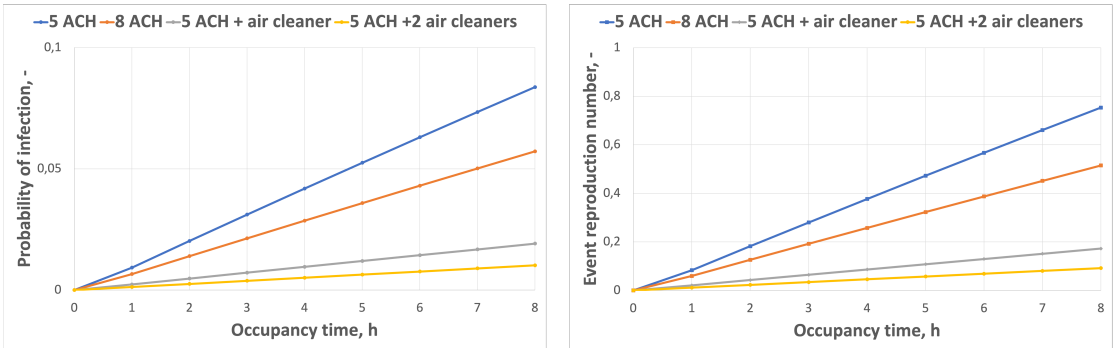
- 5 ACH ventilation consistent with the PTS guideline (Region Jonkoping County, 2023d)
- 8 ACH ventilation consistent with the healthcare hygiene guideline (Swedish Society for Healthcare Hygiene, 2025)
- 5 ACH + one air cleaner
- 5 ACH + two air cleaners

4.2.1 Model room

The model assumes a 25 m^2 room with ten occupants, which is consistent with (Region Jonkoping County, 2023d), where one individual is infected with the Omicron variant of COVID-19. Breathing and speaking rates corresponding to typical office activity were assumed. The base ventilation in the room is 5 ACH for the base scenario and then increased to 8 ACH. Adding one air cleaner with a CADR of 400 l/s to the base case of 5 ACH adds 21.3 ACH, which results in 26.3 ACH. Adding two air cleaners therefore adds 42.6 ACH and results in 47.6 ACH.

4.2.2 Results

As seen in Figure 4.7, the risk of infection reduced as the ventilation rate increases. Installing one electrostatic air cleaner reduces the probability of infection by approximately 77% compared to the baseline case with 5 ACH ventilation. Results represent theoretical relative risk reductions, not absolute infection probabilities. The



(a) Probability of infection

(b) Event reproduction number

Figure 4.7: Risk of infection based on the REHVA calculator

results indicate that increasing ventilation from 5 to 8 ACH yields only moderate reductions in infection risk, whereas the addition of a single air cleaner provides a substantially larger effect. This highlights the diminishing returns of ventilation compared to targeted air cleaning.

4.2.3 Sensitivity analysis

Influence of CADR: Figure 4.8 shows the probability of infection reduction when the air cleaner has a CADR of 300-480 l/s. The reduction ranges from 70-80 % which strengthens the choice of 400 l/s as a representative value.

Influence of quanta emission rate: The infection risk predicted by the REHVA model depends strongly on the quanta emission rate, which varies with both the infectious disease and the activity level of the occupants. More contagious diseases or activities involving heavier breathing, such as physical exercise, result in higher quanta emission rates and therefore increased infection risk. The relative reduction in infection probability achieved by installing an air cleaner is not constant for all diseases or activities. However, the reduction remains proportional to the quanta emission rate, as illustrated in Figure 4.9.

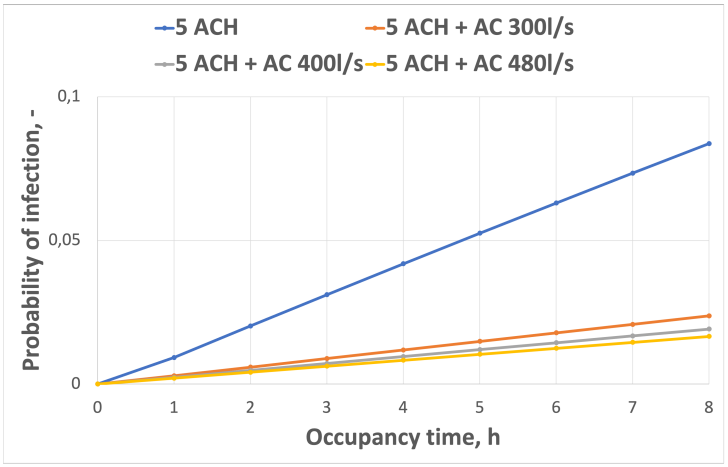


Figure 4.8: Probability of infection reduction using different CADR capacities.

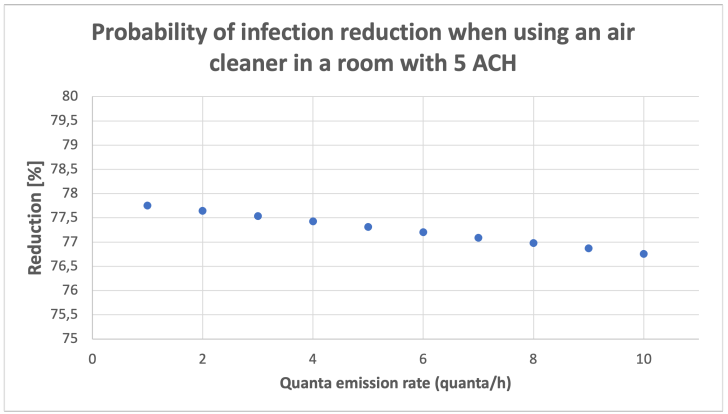


Figure 4.9: Reduction of probability of infection estimated to occur by the use of one air cleaner after 8 hours in a room with 5 ACH ventilation rate depending on quanta emission rate. Important to note that the difference is very small, the values on the y-axis are between 75 and 80 %

4.2.4 Hypothesis for field study

The modelling results indicate that increasing ventilation from 5 ACH to 8 ACH reduces infection risk only moderately. In contrast, the installation of one air cleaner provides a substantially larger reduction in both the probability of infection and the event reproduction number. Based on the laboratory experiments and the infection-risk modelling, the following hypothesis is formulated for the field study: Installing an electrostatic air cleaner in a hospital waiting room will provide an equivalent air change rate comparable to or greater than the increase from 5 ACH to 8 ACH ventilation, thereby significantly reducing airborne infection risk without increasing the mechanical ventilation airflow. This hypothesis will be tested through field measurements conducted in a hospital waiting room environment.

4.3 Ozone levels

According to the Swedish standard SS-EN 60335-2-65 for household and similar electrical appliances with particular requirements for air-cleaning appliances states that "the ozone concentration produced by air-cleaning appliances shall not be excessive" (“Household and similar electrical appliances – Safety – Part 2-65: Particular requirements for air-cleaning appliances”, 2003). This means that in a laboratory test where the walls are covered with polyurethane sheet and the appliance is supplied with rated voltage for 24 hours, the ozone level should not exceed 50 ppb. The room is supposed to be maintained at approximately 25 °C and 50 % relative humidity, which is consistent with laboratory test conditions which were 21.7 °C and 28% relative humidity. During the experiment the ozone level in Gothenburg city was 25-50 ppb (City of Gothenburg, 2026). The measuring instrument is a Dual Beam Ozone Monitor which was calibrated the day before the measurements, see Appendix A. The experiment setup can be seen in Figure 4.10.

4.3.1 Results

The maximum measured ozone concentration was 18 ppb, as seen in Figure 4.11. Accounting for a baseline level of 6 ppb, this corresponds to a net increase of 12 ppb, which is well below the 50 ppb limit defined in SS-EN 60335-2-65, indicating that the air cleaner operates within safe limits under the tested conditions.

4.4 Ionisation

Ionisation as air cleaning with no filter is an alternative way of reducing particles and killing bacteria. The ionisator gives off negative ions which attaches to bacteria and particles and charges them. The charged particles clump together and sediment and in that way they are removed from the breathing air. The good thing about ionisation is that they make no noise and they don’t require cleaning like filters do.

4.4.1 Results

Table 4.2 shows the average particle levels during the four cases.

The results show that air cleaning with ionisation provides a small benefit compared to no air cleaning, see Figure 4.12. However, electrostatic air cleaning in Figure 4.13a compared to no air cleaning in Figure 4.12a significantly reduces particle concentrations compared to ionisation alone. The addition of ionisation to electrostatic

Figure 4.10: Experiment setup

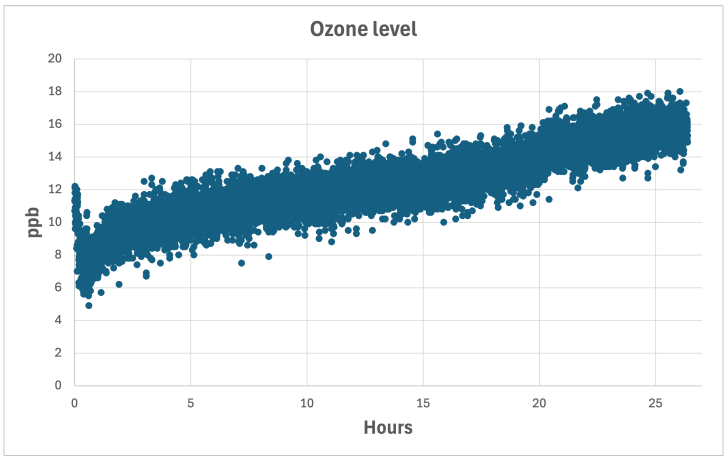
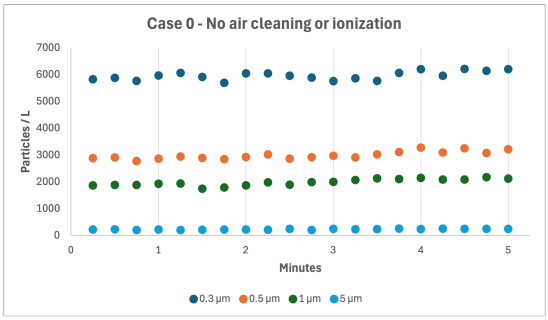


Figure 4.11: Ozone experiment

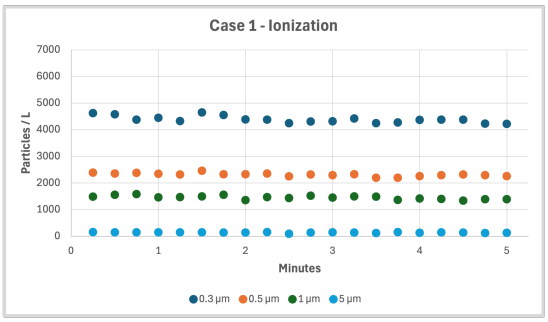
Table 4.2: Average particle concentrations for each case.

Nr of particles / l	$> 0.3\ \mu m$	$> 0.5\ \mu m$	$> 1\ \mu m$	$> 5\ \mu m$
Case 0 - zero level test	5980	3010	2000	240
Case 1 - ionisation	4360	2300	1470	140
Case 2 - air cleaning	130	80	60	10
Case 3 - air cleaning + ionisation	130	90	60	15

air cleaning provides only marginal additional benefit, see Figure 4.13, suggesting that filtration is the dominant removal mechanism.

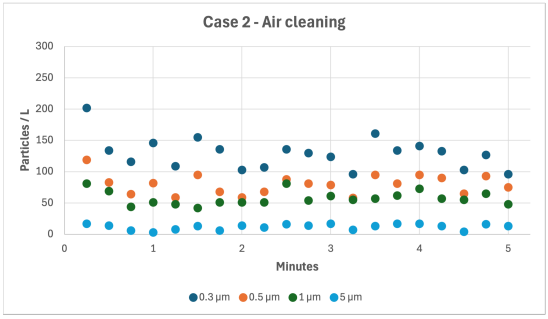


(a) Particle levels for Case 0: No air cleaning and no ionisation.

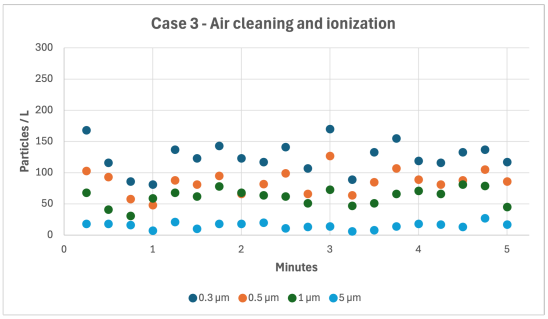


(b) Particle levels for Case 1: Ionisation.

Figure 4.12: Particle levels for Case 0 and Case 1.



(a) Particle levels for Case 2: Only air cleaning



(b) Particle levels for Case 3: Air cleaning and ionisation.

Figure 4.13: Particle levels for Case 2 and 3.

The bacteria levels can be seen in Table 4.3.

Table 4.3: Bacteria levels for each case in CFU / m^3

	CFU
Case 0 - zero level test	588
Case 1 - ionisation	344
Case 2 - air cleaning	116
Case 3 - air cleaning and ionisation	75

Figure 4.14 shows the reduction in percentage for each case. It is clear that ionisation works best for large particles and bacteria, and electrostatic air cleaning works best for smaller particles. The combination of ionisation and electrostatic air cleaning is only slightly beneficial for bacteria reduction, however, electrostatic air cleaning is beneficial overall.

4.5 Energy

There are two main air cleaners which are used during the field testing which can be seen in Table 4.4. Air cleaner 2 has a lower capacity and higher energy demand. This

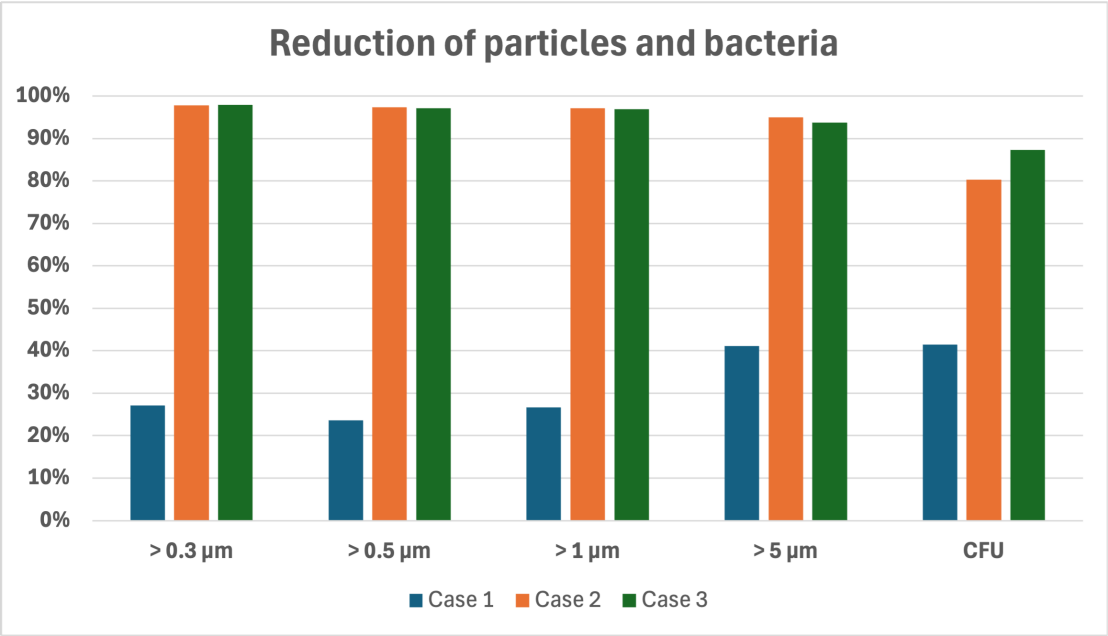


Figure 4.14: Reduction of particles and bacteria levels for each case relative to Case 0 without air cleaning or ionisation.

	CADR $[m^3/h]$	Power [W]
Air cleaner 1	1400	70
Air cleaner 2	850	106

Table 4.4: Energy levels of the different air cleaners

is most likely due to the fan in AC2, which is older than the one in AC1. For the purpose of simple energy calculations and estimations regarding air quality and energy consumption, a mean value will be used. 1125 m^3/h and 88 W corresponds to: 1000 m^3/h and 78 W. A common measurement of the fans electric efficiency is called SFP, specific fan power, in kW/m^3/s, which in this case is approximately 0.25 kW/m^3/s. This value is significantly lower than what is requested in the Swedish building code (Boverket, 2020). The air cleaners provide high CADR values at relatively low power consumption, indicating a favourable ratio between air cleaning performance and energy use compared to increased ventilation.

5 Field Results

This chapter presents the results from the field measurements from the children's emergency waiting room at Karolinska Universitetssjukhuset in Stockholm, focusing on the effect of electrostatic air cleaners on particle and bacterial concentrations, as well as noise and energy performance. Three cases with increasing equivalent air change rates were analysed to evaluate the relationship between airflow and air quality improvement.

5.1 Particles and bacteria

Three different cases were tested that correspond to different amounts of air changes to estimate whether higher flowrates improve the air quality. All cases also uses the base ventilation in the building corresponding to approximately a total of 2 ACH. The concept of ACH in the waiting room is theoretical since in practice, the doors to the corridor are open and the actual air changes are complex to calculate. The three different cases, including base ventilation were:

- **Case 1:** Air cleaner 1 and 2. Results in 7.7 theoretical ACH.
- **Case 2:** Air cleaner 1,2 and 3. Results in 10.3 theoretical ACH.
- **Case 3:** Air cleaner 1,2,3,4 and 5. Results in 12.2 theoretical ACH.

5.1.1 Case 1: Approximately 7.7 ACH

Figure 5.1 shows the FP levels for a representative day for Case 1. The secondary y-axis shows the number of occupants in the room during the day and vertical lines mark when the air cleaners are turned on and off. The figure shows clearly how the particle concentrations significantly decrease as the air cleaners are turned on, and does not depend on the number of occupants.

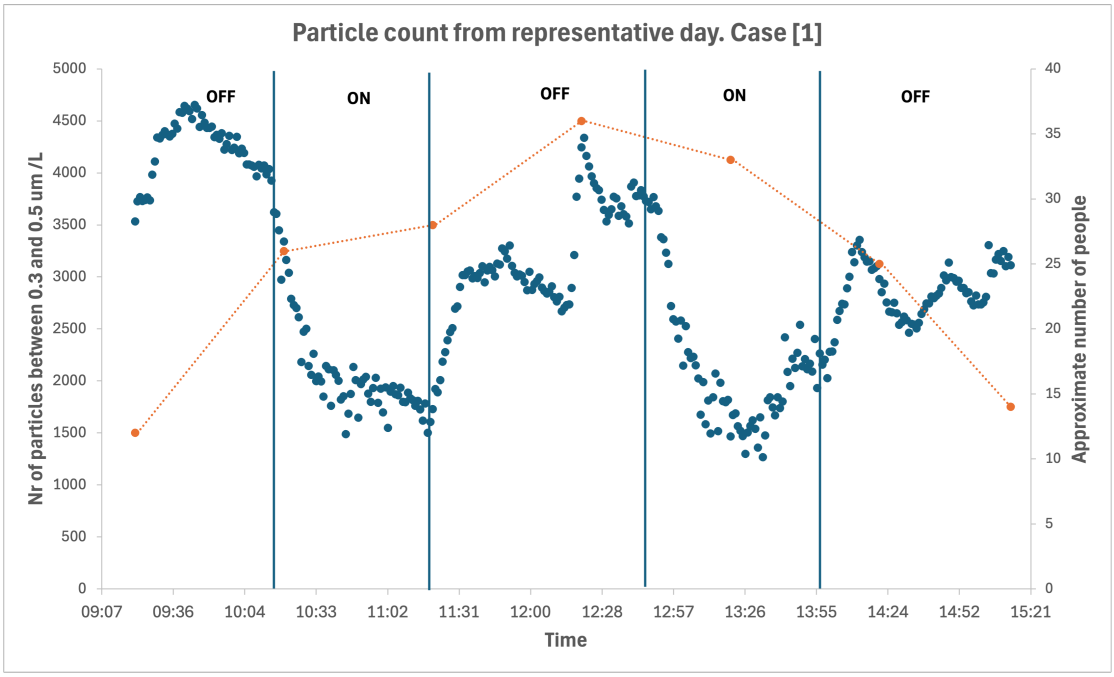


Figure 5.1: Representative day of Case 1. Nr of particles between 0.3 and 0.5 μm and nr of people during one day.

Table 5.1 shows the average particle and bacteria concentrations for when the air cleaners are on or off. The reduction can also be seen in the table.

	Unit	OFF	ON	Reduction
CFU	CFU/m^3	261	116	56 %
UFP	Particles/cm^3	603	403	33 %
FP	Particles/l	3743	2408	36 %
PM2.5	$\mu g/m^3$	3.7	1.8	53 %
PM10	$\mu g/m^3$	7.9	4.7	40 %

Table 5.1: Case 1 average values of particles and bacteria ON vs OFF

Figure 5.2 is a box plot of CFU levels when the air cleaners are in operation and when they are turned off. As seen in the figure there is a significant reduction and the variation is smaller for Case 1.

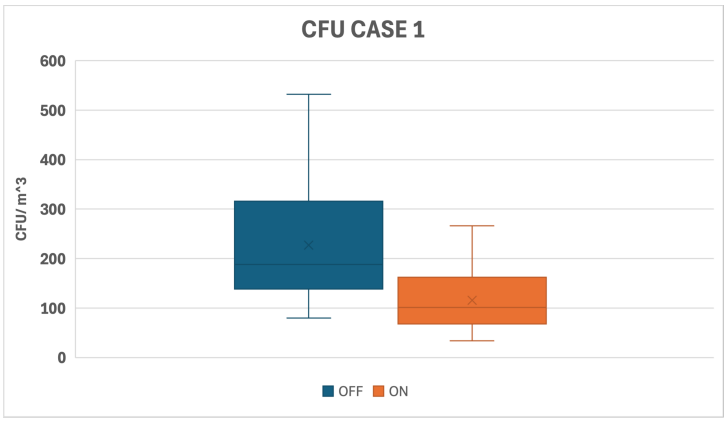


Figure 5.2: Bacteria concentrations for Case 1.

5.1.2 Case 2: Approximately 10.3 ACH

Figure 5.3 shows a representative day for Case 2. It is clear how the operation of air cleaners significantly reduce the number of particles, however it is not as clear in this case that it is independent from the number of occupants.

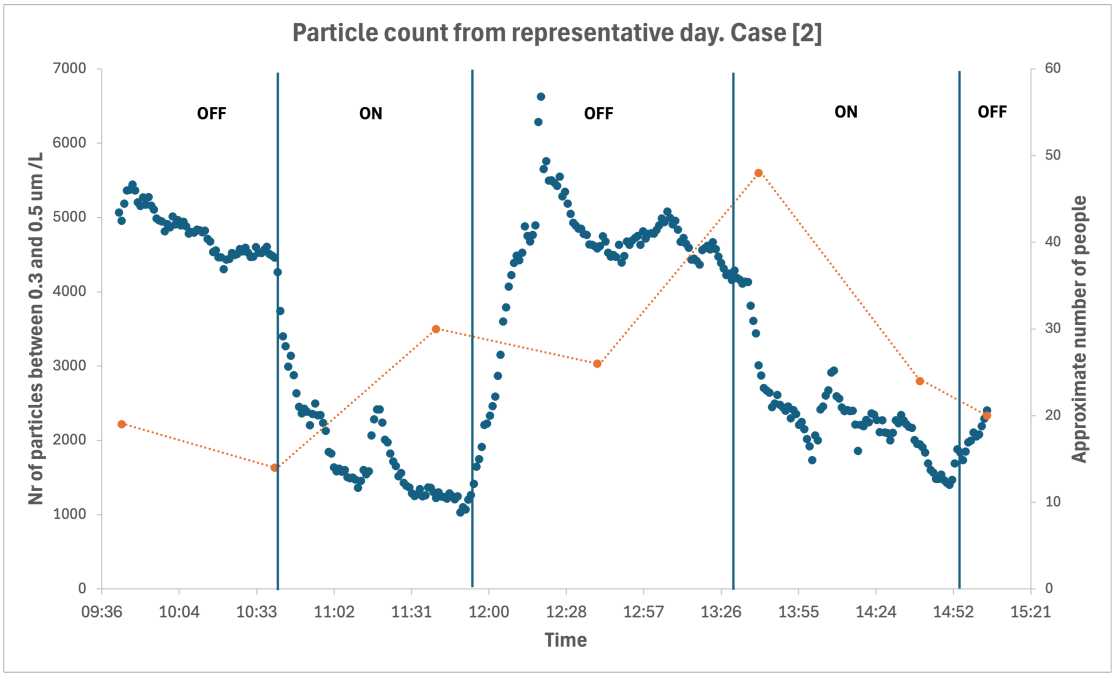


Figure 5.3: Representative day of Case 2. Nr of particles between 0.3 and 0.5 μm and nr of people during one day.

Table 5.2 shows the average values for particle and bacteria levels and reduction, which is similar to Case 1.

Figure 5.4 shows a box plot of CFU levels for Case 2. The air cleaners have a clear impact on bacteria levels. However, the variation for OFF in this case is significantly larger, this can depend on number of occupants.

	Unit	OFF	ON	Reduction
CFU	CFU/m^3	324	188	49 %
UFP	Particles/cm^3	727	456	37 %
FP	Particles/l	3041	1393	54 %
PM2.5	$\mu g/m^3$	3.2	1.4	56 %
PM10	$\mu g/m^3$	8.3	4.4	47 %

Table 5.2: Case 2 average values of particles and bacteria ON vs OFF

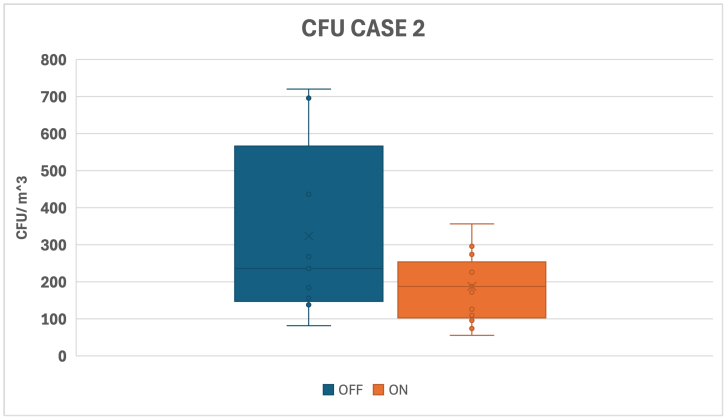


Figure 5.4: Bacteria concentrations for Case 2.

5.1.3 Case 3: Approximately 12.2 ACH

Figure 5.5 shows a representative day for Case 3. The first time the air cleaners are turned on, it is clear that the number of occupants does not influence the decrease in particles. However, for the second time the number of particles also correlate with the number of occupants.

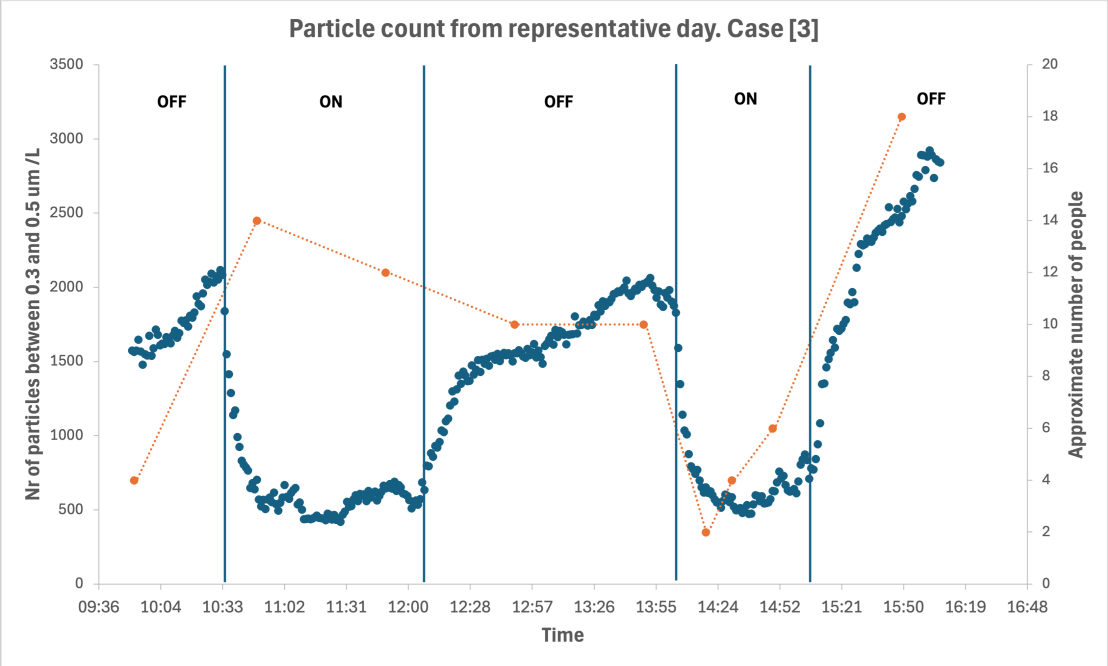


Figure 5.5: Representative day of Case 3. Nr of particles between 0.3 and 0.5 μm and nr of people during one day.

Table 5.3 shows the average values for bacteria and particle concentrations as well as reductions for Case 3.

	Unit	OFF	ON	Reduction
CFU	CFU/m^3	153	78	49 %
UFP	Particles/cm^3	443	198	64 %
FP	Particles/l	3019	1093	64 %
PM2.5	$\mu g/m^3$	2.1	0.6	71 %
PM10	$\mu g/m^3$	6.0	2.4	60 %

Table 5.3: Case 3 average values of particles and bacteria ON vs OFF

Figure 5.6 shows a box plot for bacteria concentrations, similar to Case 2, the variation for no air cleaning is quite large but there is a significant reduction in bacteria concentrations when the air cleaners are turned on.

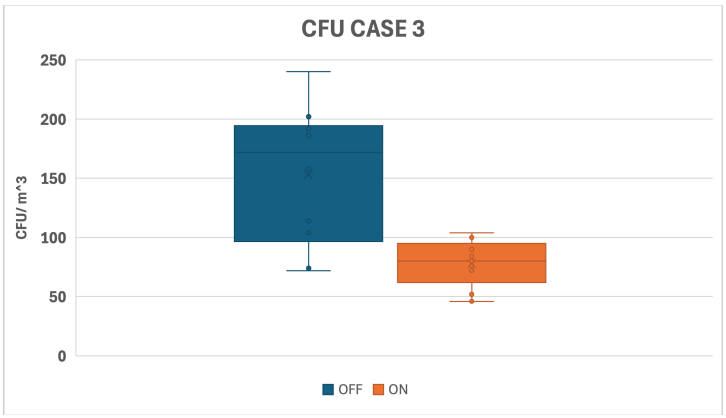


Figure 5.6: Bacteria concentrations for Case 3.

5.1.4 Summary

As seen in Figure 5.7, the increase in air changes that Case 2 and 3 provides does not influence the decrease in CFU, this could be due to the fact that bacteria is highly linked to occupants, and not air mixing. However, the number of UFP and FP are clearly dependent on the number of air changes per hour. Safe levels for waiting rooms or general hospital areas are 1000 CFU according to (Nevalainen & Morawska, 2009), which is above the measured values for all cases. However, this value should not be an indicator for safe levels since the risk of infection is highly dependent on type of infection and how receptible the patient is.

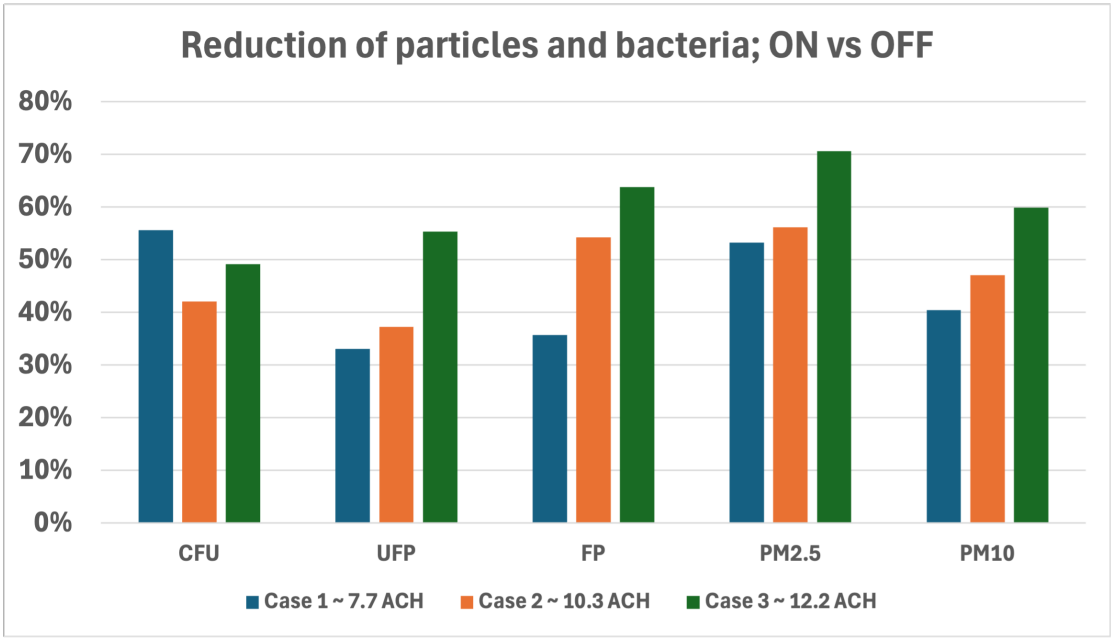
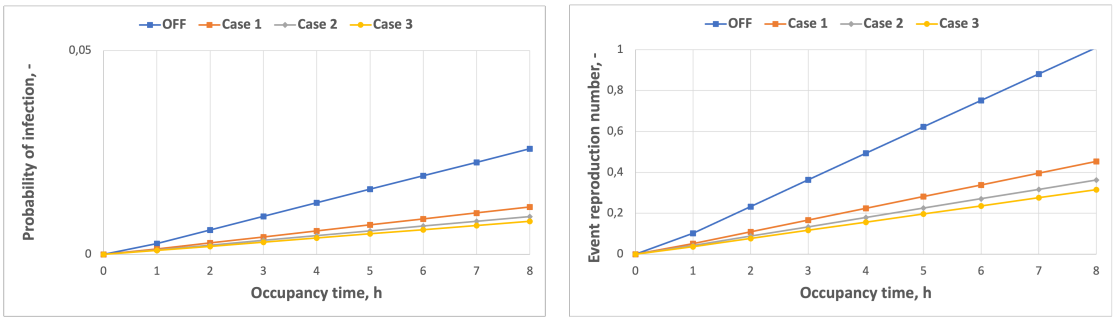


Figure 5.7: Reduction in percentage for each case

5.1.5 Theoretical risk of infection

Modeling of the field study using the REHVA calculator assuming that the waiting room is closed to the hallway and there are 40 occupants, which is the number of people at which the ventilation is designed to increase. Assuming one occupant is

infected with the Omicron COVID-19 variant, the probability of infection and the event reproduction number decreases as seen in Figure 5.8. The reduction for each case after 8 hours can be seen in Table 5.4.



(a) Theoretical probability of infection. **(b)** Theoretical event reproduction number.

Figure 5.8: Probability of infection and event reproduction number.

Table 5.4: Reduction of probability of infection and event reproduction number for each case.

	Reduction
Case 1 ~ 7.7 ACH	55%
Case 2 ~ 10.3 ACH	64%
Case 3 ~ 12.2 ACH	69%

5.2 Noise

Sound levels were measured for Case 1 with approximately 7.7 ACH. The placement of the air cleaners can be seen in Figure 5.9 and the result can be seen in Table 5.5

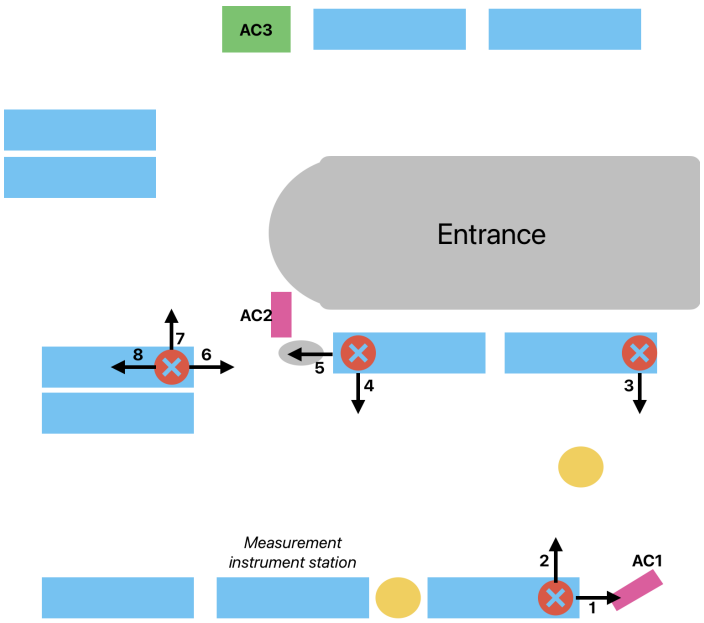


Figure 5.9: Placement of the air cleaners during the noise level test.

Table 5.5: Noise (dB(A) and dB(C)) from air cleaners. Case 1. The values in parenthesis represents AC2 at 100%, normal operations is at 80%.

Location	Air cleaners OFF		Air cleaners ON		Difference	
	dB(A)	dB(C)	dB(A)	dB(C)	Δ dB(A)	Δ dB(C)
1	43.5	60.5	51.8 (53.5)	62.2 (62.7)	8.3 (10)	1.7 (2.2)
2	44.4	54.4	50.4 (52.9)	60.4 (63.1)	6 (7.5)	6 (8.5)
3	40.9	58.5	50.8 (52.5)	61.4 (63.9)	9.9 (11.6)	2.9 (5.4)
4	42.9	60.4	51.6 (54.0)	62.1 (67.0)	8.7 (11.1)	1.7 (6.6)
5	40.1	57.1	51.1 (57.6)	63.2 (68.8)	11.0 (17.5)	6.1 (11.7)
6	46.1	54.2	52.5 (57.9)	61.2 (66.3)	6.4 (11.8)	7.0 (12.1)
7	46.4	54.8	52.4 (57.0)	60.2 (64.9)	7.8 (10.6)	5.4 (10.1)
8	45.9	54.1	50.2 (51.0)	60.0 (60.9)	4.3 (5.1)	5.9 (6.8)

The increase in sound levels (approximately 4–11 dB(A)) may be noticeable in a healthcare environment and could affect acoustic comfort. However, the levels remain within typical ranges for occupied spaces: WHO notes that normal speech is typically around 50 dB(A) at 1 meter distance (Naturvårdsverket, 2021). This suggests that the air cleaners are acceptable for practical use, depending on placement and operating mode.

5.3 Energy

According to the property management organization, the electricity consumption for the waiting room's basic ventilation amounts to approximately 3.1 MWh per year, which corresponds to 2 ACH. The forced ventilation activates when the CO_2-levels reach 800 ppm. This did not occur during the field testing. The forced ventilation doubles the power requirements and corresponds to a total of 3.5 ACH. To achieve a significant reduction in particle and bacteria concentrations and meet the recommendations from (Swedish Society for Healthcare Hygiene, 2025), one could implement air cleaners to reach 8 ACH which would need approximately 550 kWh per year if they run for 8 hour per day, and 2 MWh if they run all the time. This would significantly decrease energy usage as well as reduce the risk of infection.

The results indicate that achieving similar air quality improvements through increased ventilation would require substantially higher energy use compared to air cleaning. The estimated annual energy use of approximately 550 kWh for air cleaners is significantly lower than the additional energy required to increase ventilation rates, highlighting the energy efficiency of the proposed solution.

6 Discussion

This thesis investigated the effectiveness of electrostatic air cleaning in reducing airborne particle and bacterial concentrations in healthcare environments, with the aim of evaluating air cleaning as a complement to, or a substitute for, increased mechanical ventilation. The study combined laboratory experiments under controlled conditions, infection risk modelling using the REHVA Wells–Riley calculator, and a field study in the children's emergency waiting room at Karolinska Universitetssjukhuset. The discussion below addresses each research question in turn and then reflects on the methodological choices, the limitations of the study, and the broader societal, ethical and ecological implications of the findings.

6.1 Air quality performance

Electrostatic air cleaning resulted in substantial reductions in airborne particle concentrations under both laboratory and field conditions. In the laboratory, the measured CADR was approximately 300–480 l/s depending on the instrument and particle source, with the lowest values recorded by the P-Trak. This is consistent with the size-dependent removal characteristics of electrostatic cleaners: capture efficiency is generally lower for the ultrafine (20–100 nm) fraction the P-Trak primarily measures, and higher for the submicron range captured by the AeroTrak and DustTrak. In the field, particle reductions ranged from 33 % (UFP, Case 1) to 71 % (PM2.5, Case 3) and increased with the number of cleaners deployed. Bacterial reductions were also clear (42–56 % CFU across the three cases) but were less dependent on the number of air changes than the particle reductions. This is intuitive: CFU concentrations are dominated by the presence and movement of occupants close to the sampler, whereas fine and ultrafine particles distribute more uniformly and respond more directly to the bulk air-exchange rate. The implication is that for bacteria, placement of the cleaner near the dominant emission source may matter as much as the total CADR, a hypothesis worth testing in future work. The choice of 400 l/s as a representative CADR for the infection risk modelling is therefore a deliberate compromise. It corresponds to the instruments measuring particles in the 0.3–1 μm range, which overlaps with the size of bacteria and many virus-laden droplet nuclei. The fact that CFU reductions in the field correlated better with the larger-particle CADR values than with the P-Trak value gives some confidence in the choice, but a sensitivity analysis using the full 300–480 l/s envelope would strengthen the modelling claims.

6.2 Infection risk

Infection risk modelling using the REHVA calculator suggested that the addition of a single electrostatic air cleaner to the baseline ventilation rate of 5 ACH reduces the probability of long range airborne infection by approximately 77 % over an 8-hour exposure, compared to only a moderate reduction obtained by increasing mechanical ventilation from 5 to 8 ACH. Modelling of the actual field-study cases gave reductions of 55 %, 64 % and 69 % for Cases 1 ~ 7.7 ACH , 2 ~ 10.3 ACH and 3 ~ 12.2 ACH respectively, monotonically increasing with the equivalent ACH. These figures support the practical claim that air cleaners are a more effective marginal investment than additional ventilation airflow once a moderate baseline has been reached, which is

consistent with the diminishing returns of ventilation reported by (Filipsson & Ekberg, 2024). However, the measured CFU reductions in the field (42–56 %) were smaller than the modelled risk reductions (55–69 %). Three factors plausibly explain the gap. First, the waiting room was not closed to the corridor; the open connection means that the equivalent ACH calculated from the cleaner CADR and the room volume overstates the actual contaminant decay rate, since fresh contamination enters continuously from adjacent spaces. Second, the Wells–Riley model and its derivatives assume a well-mixed indoor environment. The waiting room has frequent door opening, point sources of bacteria close to the floor, and people moving constantly, conditions that violate the well-mixed assumption and that no zonal correction has been applied. Third, CFU is itself a highly variable measure, dependent on the proximity of emitters to the sampler and on the timing of patient visits during the sample collection period. Taken together, these factors raise an important methodological question: is the Wells–Riley framework, even with the REHVA extensions, an appropriate tool for quantifying infection risk in open, non-uniformly mixed clinical spaces? The model remains useful for relative comparisons between scenarios (ventilation vs cleaning, more cleaners vs fewer), and the rank ordering of the three field cases is preserved between the modelled and measured results. But the absolute probabilities should be interpreted with caution. Zonal or CFD-based extensions of Wells–Riley (Aganovic et al., 2023) would give a more defensible absolute estimate in a future study.

6.3 Energy performance

The rough energy analysis suggests that reaching an equivalent of 8 ACH in the waiting room through electrostatic air cleaning requires approximately 0.55 MWh per year when the cleaners run during occupied hours, or about 2 MWh per year for continuous operation. This compares favourably with the estimated 3.1 MWh per year required by the baseline ventilation alone (2 ACH), and is substantially less than the additional ventilation energy needed to raise the mechanical air change rate from 5 to 8 ACH while including the associated heating, cooling and fan losses. The annual energy figures are simple estimates and do not include heat recovery effects on the ventilation side, which would partly offset the energy penalty of higher ACH. Conversely, they also do not include the embodied energy of the cleaner units or the energy used to wash and replace filters. A proper life-cycle energy comparison is outside the scope of this study but is recommended as follow-up work. Even though these have not been taken into account, the order-of-magnitude conclusion, that air cleaning is the more energy-efficient route to an equivalent ACH, appears robust.

6.4 Operational feasibility

The maximum ozone concentration recorded during 24-hour continuous operation of the cleaner was 12 ppb, well below the 50 ppb limit defined by SS-EN 60335-2-65 and below the prevailing outdoor ozone concentration in Gothenburg on the measurement days. The ozone risk associated with this electrostatic technology therefore appears negligible in normal operation, though long-term studies should verify that this remains true as filters age and surface chemistry changes. Sound-level measurements showed an increase of approximately 4–11 dB(A) when the cleaners were active in normal-operation mode (80 % fan speed). Measured A-weighted levels with cleaners

on were typically 50–53 dB(A), which is comparable to ordinary office background noise and within the ranges generally accepted in healthcare waiting areas. At 100 % fan speed, the increase rose to 11–18 dB(A) at some measurement points, which would likely be perceptible and may not be acceptable in all clinical settings. Cleaner placement and fan setting should therefore be selected with acoustic comfort in mind, particularly in spaces where children, sleeping patients, or staff communication are involved.

6.5 Implementation potential

Taken together, the results indicate that electrostatic air cleaning is a viable supplementary strategy for reducing airborne infection risk in healthcare facilities with high occupancy or limited ventilation capacity. The technology is energy-efficient, generates negligible ozone, and produces noise within acceptable bounds at normal fan speed. Practical implementation should consider: (i) sizing the total CADR to match the target equivalent ACH for the room volume, with a safety factor to allow for the open-connection losses observed in this study; (ii) positioning cleaners near likely emission sources rather than purely on the basis of convenience, given the importance of placement for CFU reduction; and (iii) selecting fan speed and unit count to meet acoustic targets. The technology is best understood as a complement to, not a replacement for, mechanical ventilation, which still provides the essential function of supplying outdoor air.

6.6 Comparison with prior work and alternative methods

The earlier study by Olsson and Ekberg (2024) at Kungälv hospital reported bacteria-level reductions of roughly an order of magnitude in an enclosed patient room with the same technology family, with smaller relative reductions in their open waiting room. The present results sit between those two extremes and are consistent with the conclusion that room geometry and openness to adjacent spaces are dominant factors in the effective performance of the cleaners. The Karolinska waiting room used here is more open than either of the Kungälv rooms, which partly explains the modest CFU reductions despite high theoretical CADR.

Ionisation was investigated as an alternative removal mechanism. The laboratory comparison showed that ionisation alone reduces particles by 25–40 % and bacteria by approximately 40 %, but adding ionisation to electrostatic cleaning yielded only marginal additional benefit. Filtration appears to be the dominant removal mechanism for both particles and viable bacteria. Ionisation may still be useful in contexts where complete acoustic silence is required and a moderate reduction is acceptable, but it is not a substitute for filtration in spaces where infection risk is a primary concern.

6.7 Limitations

Several limitations of the study should be noted. The laboratory CADR was determined in a single air tight room with ventilation deliberately switched off; this maximises the measurable signal but means the values represent intrinsic device performance rather than performance in a ventilated room. Different instruments produced CADR values across a 300–480 l/s range, and the modelling depends on the choice within that range. The field study covered eight days in a single ward, with

variable occupancy, weather, and outdoor air quality; no statistical inference (significance testing, confidence intervals) was performed on the ON/OFF comparisons, although the magnitude of the reductions is large enough that the qualitative conclusions are unlikely to depend on the specific test used. Infection risk was estimated through modelling rather than direct epidemiological outcomes; no claim about real-world infection rate reduction is made. The results apply to the specific cleaner family tested and to an emergency waiting room; transfer to operating theatres, isolation rooms or other contexts requires separate evaluation.

6.8 Societal, ethical, and ecological aspects

Healthcare-associated infections impose a substantial burden on patients, staff and healthcare budgets, and airborne transmission is a recognised contributor. Any technology that reduces airborne contamination at modest energy and capital cost therefore has a direct societal benefit by improving patient safety and reducing length of stay. The benefit is particularly large in resource-limited settings where mechanical ventilation upgrades are not affordable; portable electrostatic cleaners are a comparatively inexpensive intervention with measurable infection-risk reduction (Rutegård et al., 2025).

From an ecological perspective, the technology emphasises low power consumption and the use of washable rather than disposable filters, which reduces both operational energy and consumable waste compared with HEPA filtration. The estimated annual electricity use of approximately 0.55 MWh during occupied hours is small in the context of total hospital energy demand. The quiet operation supports a calm environment for patients and a functional workspace for staff. The field measurements were performed in an emergency waiting room, a setting that requires particular ethical care. No personal data on patients were recorded; only aggregate counts of occupants and ambient air-quality parameters were measured. Children and their caregivers were not approached, interviewed or identifiable in the data set, and the measurement equipment was placed unobtrusively at a single station. Permission to conduct the study was obtained from the hospital management and the relevant department head before measurements began. Researcher presence in the room was recorded as a contextual parameter. The intervention itself (switching air cleaners on or off) involves no direct interaction with patients and poses no foreseeable risk: ozone production was independently measured to be well below regulatory limits, and the cleaners were placed to avoid air currents directed at occupants.

More broadly, the design of healthcare facilities raises ethical questions about prioritisation. Spending limited capital budget on air cleaning implies not spending it elsewhere; the case for doing so rests on the comparative cost-effectiveness of infection reduction, which this thesis supports but does not by itself prove. A formal cost-effectiveness analysis linked to clinical infection rate data would be the natural next step.

7 Conclusion

This thesis evaluated whether electrostatic air cleaning can serve as an energy-efficient supplement to mechanical ventilation for reducing airborne infection risk in healthcare facilities. By combining laboratory CADR measurements, Wells–Riley infection-risk modelling and a field study in an emergency waiting room, the study provides field evidence, currently scarce in the Swedish context, that electrostatic cleaners substantially improve indoor air quality at a fraction of the energy cost of an equivalent ventilation uplift, while remaining within accepted limits for ozone and noise.

RQ 1 - Air quality performance Electrostatic air cleaning reduced particle concentrations by 33–71 % across ultrafine, fine and mass-concentration metrics, and reduced viable airborne bacteria (CFU) by 42–56 % in three field cases corresponding to equivalent air change rates of 7.7, 10.3 and 12.2 ACH. Particle reductions scaled with the number of cleaners; CFU reductions did not scale as strongly, indicating that occupancy driven bacterial sources are not fully captured by bulk air exchange metrics.

RQ 2 - Infection risk Modelled probability of airborne infection decreased by 55–69 % across the three field cases. Adding a single cleaner to a 5 ACH baseline produced a larger modelled risk reduction than raising mechanical ventilation from 5 to 8 ACH, supporting the use of air cleaning as the more effective marginal intervention once moderate ventilation is in place. Measured CFU reductions were somewhat smaller than the modelled risk reductions; the gap is attributable to the open connection between the waiting room and the corridor and to the well-mixed-room assumption underlying the model.

RQ 3 - Energy performance Equivalent air quality improvements were achieved with approximately 0.55 MWh per year per cleaner during occupied hours, considerably less than the additional ventilation energy required to reach the same equivalent ACH through mechanical means. Air cleaning is therefore the more energy-efficient route to a given equivalent ACH in the scenarios examined.

RQ 4 - Operational feasibility Ozone production reached a maximum of 12 ppb in continuous operation, well below the 50 ppb limit set by SS-EN 60335-2-65. Sound levels increased by 4–11 dB(A) at normal (80 %) fan speed, remaining within typical occupied-space ranges. Both ozone and noise are therefore acceptable for healthcare use at normal operation; full fan speed produces a larger acoustic impact and should be used selectively.

RQ 5 - Implementation potential Electrostatic air cleaning can be implemented as a supplementary solution in healthcare facilities, either as standalone room units or as components of a hybrid ventilation strategy. It is most valuable in spaces with high occupancy turnover, in older buildings with limited ductwork capacity, and in low-resource settings where ventilation upgrades are not feasible. It is a complement to mechanical ventilation, not a replacement for it: the outdoor-air function of ventilation remains essential.

Practical recommendations

- Size the total cleaner CADR to give a target equivalent of 8 ACH for the room volume, with a margin to absorb losses caused by open connections to adjacent spaces.
- Position cleaners with line-of-sight to the dominant emission sources (e.g. waiting-area seating, reception), not purely on the basis of installation convenience.
- Run cleaners at appropriate fan speed for acoustic comfort.
- Couple deployment with monitoring (CO_2, particle counts) so that performance can be verified once and rechecked periodically.
- In open spaces such as emergency waiting rooms, accept that measured reductions in CFU will be smaller than modelled reductions and plan accordingly when comparing scenarios.

Future work

- Long-term field studies across multiple ward types, patient rooms, treatment rooms, isolation rooms, to evaluate durability and seasonal effects.
- Statistical analysis of the on/off comparisons (paired tests, mixed-effects models accounting for occupancy as a covariate).
- Zonal or CFD-based extensions of Wells–Riley to handle non-well-mixed clinical spaces and to refine the absolute risk estimates.
- Linkage of air-quality improvements to clinical infection-rate data through observational or cluster randomised studies.
- Life-cycle assessment of the cleaners themselves: embodied energy, filter waste, expected service life and end-of-life disposal.

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Appendix A

Calibration report for ozone instrument

KALIBRERING AV OZONINSTRUMENT med LoF-test

IVL metod A17, ref. SS-EN 14625:2024, BIPM 2024/03

Detta blad används vanligen före filterbyte och eventuell service

Ort:	Gbg IVL lab.	Valid. datum:	2026-03-17
Datum/mätpers.:	2026-03-17 / John Andersson	Validerad av:	Henrik Fallgren

I denna mall skriver man in

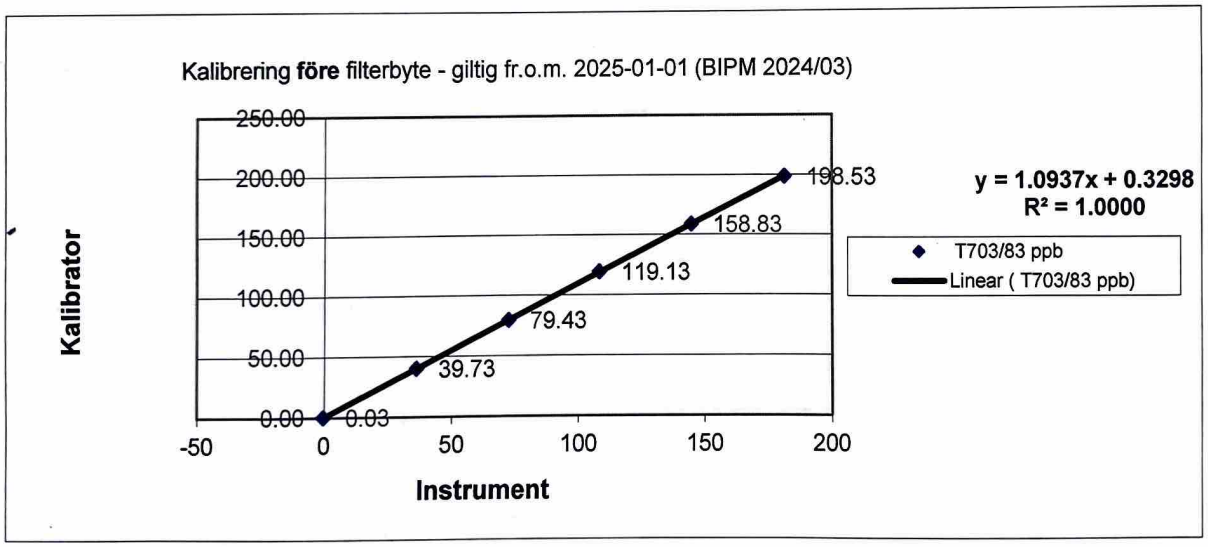
Spalt A: Instrumentets Typ/Serienr. och mätvärden

Spalt B: Kalibratorns Typ/Snr. och uppmätta värden ej justerade

Instrument / Nr.	Kalibrator	Nivå	Anteckningar	Kalibrator
2B Tech S/N 2003DB	T703/83	(info)		korr.
ppb	ppb	ppb		ppb
181.5	200	200	Slope 1.03	198.53
144.7	160	160		158.83
108.3	120	120		119.13
72.4	80	80		79.43
36.2	40	40		39.73
-0.3	0	0		0.03

Kalibrator Certifikat	Datum	Linjär (x)	Offset
(ACES, Stockholm)	2026-03-04	0.9925	0.0266
Anm.: med 2025 års faktor, ref. CCQM.O3.2019			

Resultat från senaste referenskalibrering!



Fyll i diagrammets formel (y=) k*x+m:	
LUTNING k	1.0937
OFFSET m	0.3298

Faktorn k och offset m används i databasens kalibreringstabell.

Mätvärde (x)	y=a*x-m	Kalibrator	Lack of fit
181.5	198.8	198.5	0.16%
144.7	158.6	158.8	0.15%
108.3	118.8	119.1	0.29%
72.4	79.5	79.4	0.11%
36.2	39.9	39.7	0.49%

Info: Lack of Fit (EN 14625) maximum:	*2% (4%*)*

**) 2-4 % medför åtgärdsplan!*

Förhöjt resultat enbart för lägsta mätvärdet kan ha matematisk orsak (kurvanpassning vid origo).

KALIBRERING AV OZONINSTRUMENT med test av repeterbarhet

Detta blad används vanligen efter filterbyte och eventuell service

Ort:	Gbg IVL lab.	Validerad datum:	2026-03-17
Datum/mätpers.:	2026-03-17 / John Andersson	Validerad av:	Henrik Fallgren

Avläsningar efter filterbyte och eventuella justeringar

Enhet: ppb

	Ozon	Ozon
Kalibrator	0	150
Kalibrator, korr.	0.0266	148.90
Repet.test	**Nollgas**	**Kal.gas**
1	0.30	159.6
2	-0.30	159.7
3	0.00	160.1
4	0.20	159.4
5	-0.40	160.1
6	-0.10	160.5
7	-0.20	160.0
8	0.10	159.8
9	0.20	160.2
10	-0.10	159.6
Resultat medel	**-0.03**	**159.9**

EN 14625 recommended concentration:
70 %- 80 % of the cert. range 200 ppb

Anteckningar	
Inget filter användes	
Justerad slope från 1.03 till 1.13	

EN 14625: After waiting for a period sufficient to get a stable reading, 10 individual measurements both at zero concentration and at span concentration shall be performed to calibrate the analyser.

Kalibreringsfaktorer till databas

Ozon	Ozon
M=OFFSET	K=LUTNING
0.0566	**0.9310**

Utvärdering av repeterbarhet

enligt EN 14625:2024

Span-average	diffsum	s_r (span) <= 3 ppb	Anm.:
159.9	1.02	**0.34**	

Noll-average	diffsum	s_r (noll) <= 1 ppb	Anm.:
0.0	0.48	**0.23**	

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