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The influence of mechanical ventilation and portable air cleaners upon aerosol spread in a hospital outpatients clinic

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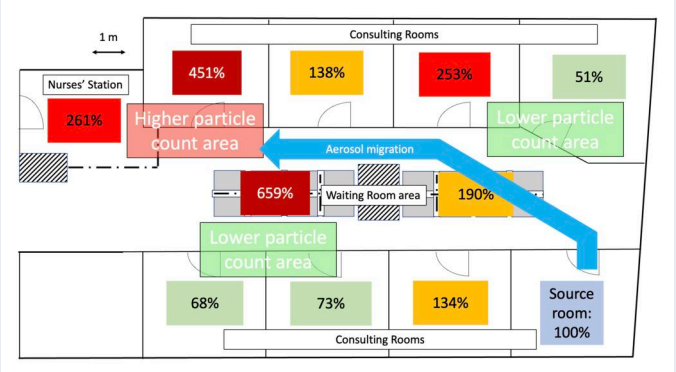
ABSTRACT

The SARS-CoV-2 global pandemic has highlighted the risk of nosocomial infections of airborne viruses to patient populations around the world. Increased use of mechanical ventilation and portable air cleaners (PACs) have been suggested as methods to mitigate this risk, but the introduction of new air flows to indoor areas can have complex and potentially unforeseen consequences. We used particle counters to investigate the effect of using built-in mechanical ventilation and/or PACs in a typical hospital outpatients' clinic upon the spread of aerosols produced by an aerosol generator. A variety of scenarios was investigated, examining particle movement to a neighboring room, throughout the whole clinic, and from one room to another at the far side of the clinic. Whilst both built-in ventilation and PACs may reduce particle migration in some scenarios by up to 96%, use of the same PACs may lead to unexpectedly increased aerosol migration of 29% between neighboring rooms, and use of built-in supply ventilation may increase aerosol migration across the clinic by up to 5.5 times. These increases are most likely due to the introduction of air flows from the outlets of these devices, providing aerosols with enough momentum to traverse the distance between relatively remote locations or creating recirculation regions that pull aerosols out of one room and push them into another. Accordingly, in order to effectively deploy these useful mitigations to their full potential and not simply displace the risk of nosocomial infection, careful consideration of placement and resultant air flow dynamics is required.

GRAPHICAL ABSTRACT



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1. Introduction

SARS-CoV-2 has highlighted the threat of airborne viruses, with nosocomial infections exacerbating the spread of these diseases, particularly to vulnerable and frail cohorts of the community (Duval et al. 2022), and severely impacting the day-to-day operation of many hospital departments (Sargsyan et al. 2023). Small ($<100\,\mu m$) exhaled droplets carrying infectious matter are likely to evaporate and remain suspended in the air, functioning similarly to aerosols (De Oliveira et al. 2021). Aerosol migration has been indicated to be one of, if not the most important modes of airborne virus transmission, with infectious matter transported long distances whilst remaining infectious (Shrimpton et al. 2021; Sheikh et al. 2022; Thuresson et al. 2022). Reducing the migration and/or build-up of these aerosols may decrease nosocomial infection of current and future airborne diseases, reducing the load on healthcare systems and protecting patients.

Built-in mechanical ventilation is the preferred method of mitigating this threat, but it is economically costly to retrofit and has a high carbon cost to run. Some existing built-in mechanical ventilation, especially older units using filter grades up to MERV 14, may not be sufficient to filter out virus particles (Mousavi et al. 2020). The 2021 NHS document "Health Technical Memorandum 03-01 Specialized Ventilation for Healthcare Premises" (HTM-03-01) advises not to focus on ventilation rates but rather air treatment rates. This guidance states that "healthcare ventilation systems will normally be 'full fresh air' either by natural, mixed mode or mechanical means". For a General Treatment Room, such as the Outpatients Clinic studied in this report, this fresh air should be supplied at a rate of 10 L/s/person, with a pressure regime that is neutral to the corridor. As per the 2023 NHS document "NHS Estates Technical Bulletin (NETB 2023/01 A)", Portable Air Cleaners (PACs) may provide a supplement to this ventilation, and can reduce the risk of airborne transmission. PACs have been shown to enhance the cleaning of indoor air after the infectious source has left the vicinity, removing all sizes of infectious SARS-CoV-2 particles from the air (Salmonsmith et al. 2023; Barnewall and Bischoff 2021; Brady et al. 2023; Cortellessa et al. 2023; Conway Morris et al. 2022; Lee et al. 2021; Rodríguez et al. 2021). One method of quantifying the ventilation or air cleaning in a room is Air Changes per Hour (ACH), with a higher ACH indicating a safer space for patients and medical healthcare workers. Pre-covid advice was for 6 ACH for a room with expected presence of healthcare professionals or patients, which PACs can help to achieve.

However, changes to air flow dynamics following the introduction/alteration of built-in mechanical ventilation or PACs are highly complex, as shown in previous CFD work (Castellini et al. 2022; Dbouk, Roger, and Drikakis 2021). Boundary conditions, supply and/or outlet flows, and physical barriers amongst other factors (such as the movement of people) can alter air flows in sometimes unexpected ways, even after seemingly slight modifications to the initial system (Chen et al. 2010; Lin et al. 2024; Ritos, Drikakis, and Kokkinakis 2024). Although these PACs are no expected to be used in designated positive pressure rooms within hospitals, changes to air flow as a result of introducing PACs require consideration to ensure that infectious particles are being removed or transported to relatively safe air volumes (i.e., outdoors), and not instead to other rooms within the hospital where patients are undergoing procedures or consultations. Built-in mechanical ventilation has already been shown to potentially spread pathogenic particles through an air duct system for as long as 20 days after being cleaned (Crimi et al. 2009). Although PACs remove the vast majority of particles that enter the internal filtration system/UV neutralization system/etc, the expelled air from the top of these units may project infectious aerosols away from the PAC before the intended particle mitigation/filtering has taken place.

Investigating the effect of built-in mechanical ventilation and/or PACs upon the migration of aerosols is an important step along the pathway to producing bespoke solutions for airborne diseases mitigation that takes into account these air flow complexities. In this work, we investigate the maximum spread of aerosols from a variety of locations within a typical outpatients' clinic in an NHS hospital (UCLH, London, UK), whilst varying the operating conditions of built-in ventilation and PACs.

2. Materials and methods

We used a previously developed and validated aerosol generator (Salmonsmith et al. 2023) to mimic a subject with an airborne respiratory disease (such as SARS-CoV-19), and aerosol detectors to represent recipient exposure. Aerosols were introduced at a constant rate into the environment using the setup described in Salmonsmith et al. (2023), which in brief was passing compressed air at 1 bar through a nebulizer (CompAIR C28P, Omron, Japan) filled with saline (9 g NaCl/1 litre deionized water), before going through the tubing of an android-like assembly, a VirtuAL hUman exhAlation replicaTOR (VALUATOR)

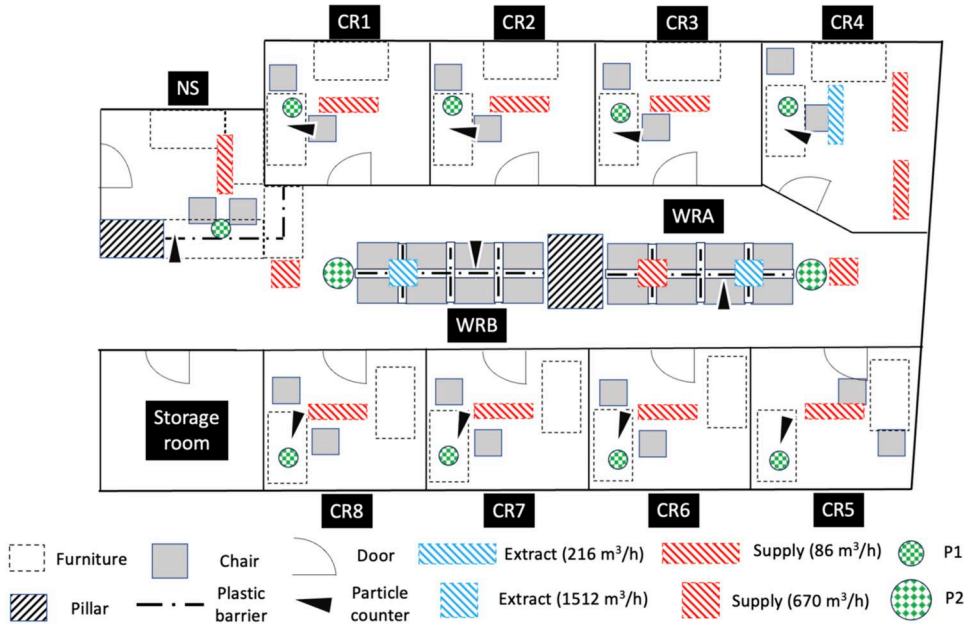

Figure 1. Clinic and mitigation layout. Locations are labeled as Nurses' Station (NS), Consulting Room (CR), or Waiting Room (WR). Supply and extract are all mechanical built-in ventilation. P1 is a small portable air cleaner (PAC) with HEPA filtration and P2 is a larger one, also with HEPA filtration. The Storage Room in the bottom left was not opened at any time. See methods for description of how devices were used and whether doors were open/closed for each experiment.

to exit at a height of 1.2 m, equivalent to the exhalation height of an adult human sitting down. Emergent aerosols had a mass median aerodynamic diameter of 3 µm, a peak and mean aerosol velocity of 1.2 m/s and 0.45 m/s, respectively, consistent with previous studies on human aerosol production (Ho et al. 2021; Salmonsmith et al. 2023). A graph of typical aerosol diameter distribution is given in the online Supplemental Information (Figure S2). It should be noted that this distribution only captures the smallest particles of the human range (0.1–1000 µm (Bagheri et al. 2022)) that are still capable of carrying an infectious dose of COVID-19 (Ho et al. 2021). These smaller particles would also be expected to travel further distances than larger, heavier particles (De Oliveira et al. 2021).

Aerosol density was over 1000× higher than that exhaled by a human (number), enabling the spread of aerosols to be detected by a local increase in aerosol concentration compared to the baseline value before experiment initiation. From this point of view it is worth remarking that in our previous work on aerosol clearing through PACs in a consulting room (CR) we demonstrated that initial aerosol concentration and density does not affect the clearing rate and half-life time of aerosols concentration decay in time (Salmonsmith et al. 2023).

Aerosol dispersion experiments were carried out *in situ* in an Outpatients clinic at UCLH NHS Foundation Trust, London, UK, which consisted of a central Waiting Room (WR), 8 surrounding CRs, a Nurses' Station (NS), and a storage room (Figure 1). This clinic was connected *via* a permanently open passageway to a corridor leading to the rest of the hospital. The door to the storage room was closed for all experiments. Whether the doors to each of the CRs were open or closed depended on the specific experiment, as described in the relevant section. Each CR and the NS had a volume of approximately 35 m^3, whilst the WR volume was approximately 154 m^3. The total clinic volume was therefore approximately 470 m^3. The outpatient clinic is designed with no pressure differentials between the CRs and the WR. Experiments were undertaken at night and weekends with no staff or patients present. The researchers carrying out these experiments were in the area of interest in between runs, in order to ensure the aerosol level had returned to a baseline level and alter the mitigations for the next experiment, but no researchers were present during the aerosol generation/measurement portion of the experiments.

The Supply air system provides full fresh air with no recirculation from a common Air Handling Unit (AHU) utilizing G4 and F7 filters. The AHU serves the whole of the hospital floor the outpatients' clinic is situated on. The air is delivered into the individual CR *via* active chilled beams and the WR *via* supply grilles, and then extracted from the WR area *via* ceiling mounted extract grilles and from CR4 by an

extract beam (i.e., the air is extracted from the department and directly discharged to atmosphere). The WR area and staff base also benefit from mechanical supply ventilation delivered by ceiling mounted 4-way blow louver face diffusers. Ventilation is supplied at a design volume flow rate of either 86 m^3/h or 670 m^3/h and extracted at 216 m^3/h or 1512 m^3/h (dependent upon the size of the vent for both supply and extract), arranged as indicated in Figure 1. The total air delivery and extraction are approximately 3000 m^3/h, which equates to approximately 6 air changes per hour throughout the clinic. Airflow rates were estimated based on measurements with a hot wire anemometer (RS-8880, RS Group, UK) at the start and end of each day of experiments. Supply airflow was found to vary from 93 to 94 m^3/h (for the smaller supply system, compared to a design flow rate of 86 m^3/h) and 530–756 m^3/h (for the larger supply, compared to a design flow rate of 670 m^3/h). Extract airflow was found to vary from 249 to 256 m^3/h (for the smaller extract system, compared to a design flow rate of 216 m^3/h) and 1174–1680 m^3/h (for the larger extract, compared to a design flow rate of 1512 m^3/h).

The temperature and humidity of the clinic was taken in several locations before and after each experimental run and remained between 22 °C–25 °C and 50%–58% rH respectively. As experiments were done in the evenings or at weekends when the outpatients' clinic was empty, the temperature is expected to be slightly cooler than daytime temperatures during the week. Unless switched off as per an experimental constraint, the ventilation settings during the experiments were consistent with daytime hours during the week.

Two different types of PAC were used in this research, a smaller air filter device, P1 (Clean Air Delivery Rate, CADR, capability of 201 m^3/h, Core 200S Smart True HEPA Air Purifier, Arovast Corporation, CA, USA); and a larger air filter device, P2 (CADR of 466 m^3/h, LV-H133 Tower True HEPA Air Purifier, Arovast Corporation, CA, USA). In order to reduce the noise from these devices during operation, when P1 and P2 were used in the 15 min aerosol generation period of the experiments, they were both used on their medium setting (2 of 3), providing a flow rate of 1.1 m^3/min (a CADR of 66 m^3/h) and 2.2 m^3/min (a CADR of 132 m^3/h), respectively, with these positioned as indicated in Figure 1. Noise levels were 47 dB or less at a distance of 0.5 meters. Mechanical ventilation and PACs were located as indicated in Figure 1, although it is important to note that not all of these units were switched on for each experimental run. The precise configurations are described for each experiment.

Aerosols were detected and quantified using handheld laser diode Particle Counters (PC) (AeroTrak 9306, TSI Incorporated, MN, USA), operating under standard manufacturer's settings of 2.83 l/min, sizing and counting particles into 6 bins covering a range of 0.3–25 µm. 60 s samples were taken over, with no pause in-between consecutive samples. The inlet tube of each PC was placed at a height of 1.2 m, representing the approximate height of a seated adult's mouth.

The experimental protocol was the following:

- A baseline of aerosol concentration – the mean of five consecutive samples - was taken before any seeding from VALUATOR, in order to establish a background count for each series of experiments.
- Aerosolised saline particles were then generated at a constant rate for 15 min per experiment run, with built-in and portable mitigations configured as needed for a specific run. 15 min was chosen as this is the standard length of a consultation in one of the CRs in the clinic.
- After this period, the aerosol source was stopped, and aerosol clean-up began. The aerosol concentration was regularly measured at 1 min intervals with all PACs switched on at maximum flow rate setting to aid aerosol clean-up, until the aerosol concentration level returned to the baseline measured before starting the next experiment run. PACs were then set to the setting required for the configuration required for the next experiment's aerosol generation.
- Particle counts are referenced to in two ways in this article
  - Cumulative particle count, the sum of all 6 particle bin counts over the 15 minute-long period for a particular particle counter.
  - Normalized particle count, where the cumulative particle count for a specific location is presented as a proportion of the cumulative particle count for the location where VALUATOR is positioned.

2.1. Run specific mitigation setups

Three different setups were considered to investigate and identify different particle movement pathways.

2.1.1. Particle migration to a neighbouring room

The first experiment was designed to investigate particle movement from a patient or medical professional in a CR to the immediately adjoining WR and CR next door, in order to see how effective various mitigation strategies (open or closed doors, PACs in various locations) were at preventing aerosol migration

Table 1. Particle migration to a neighbouring room experiment configuration.

Experimental Run	CR7 Doors	CR8 Doors	P1 (small) PAC in CR	P1 (small) PAC at Nurses' Station	P2 (large) PAC in Waiting Room Areas
1	Open	Open	–	–	–
2	**Closed**	**Closed**	–	–	–
3	Open	Open	–	–	✓
4	Open	Open	✓	✓	–
5	Open	Open	✓	✓	✓

Experiments were undertaken using five different configurations, with doors open or closed and portable air cleaners (PAC) in consulting rooms (CR) and waiting room areas switched on (indicated by '✓') or off (indicated by '–'). mechanical ventilation, supply and extract, was switched on throughout all experiments.

from the source CR (CR8) to close by locations. There were 2 adjoining WR, shown in Figure 1 as WRA and WRB.

Two neighboring CRs (CR7 and CR8), WRB, and NS were used. VALUATOR was positioned in the center of CR8, facing toward the door, simulating the worst-case scenario for aerosol migration from the room. Supply and extract mechanical ventilation were switched on throughout the experiments.

Particle counters were turned on in CR7, WRB, and NS and aerosol generation runs were carried out for each of the mitigation configurations indicated in Table 1. The CR doors were open unless indicated otherwise in Table 1. All other devices in the rest of the clinic (i.e., in WRA and CRs 1–6) were switched off throughout this experiment.

2.1.2. Particle migration across full clinic

The second set of experiments analyzed the entire clinic area, including all CRs, both WRs, and NS, to study the risks of aerosol migration to any patient or medical professional who happens to be in any part of the clinic at the same time as an infected person. VALUATOR was positioned in the center of a different CR for each run, facing toward the door. Particle counters were positioned in all CRs, both WRs, and the NS. Supply and extract mechanical ventilations were switched on throughout the experiments. CR doors were all open throughout the experiment.

All the small PACs in CRs 1–8 and NS and the large PACs in WRA and WRB were switched on throughout.

An aerosol generation run was carried out with a VALUATOR placed in each CR in turn.

2.1.3. Cross-clinic particle movement

To further investigate the findings from the "Particle Migration Across Full Clinic" setup, the final set of experiments involved two CRs diagonally opposite each other in the clinic (CR1 and CR5), and the two WRs, examining the transportation of aerosols from a CR in one corner of the clinic to the CR in the furthest opposite corner, which had already been shown to have the potential of high aerosol migration, in order to find out if some of the mitigations introduced to improve overall ACH were potentially increasing aerosol migration to specific (and perhaps relatively remote) areas of the clinic. A series of experimental runs was carried out in each of these locations, with VALUATOR positioned:

- in the center of a CR for each CR run, facing toward the door
- next to the relevant particle counter in the WR for each WR run, facing toward the nearest wall (i.e., representing a patient sitting down in one of the WR seats, facing away from the center of the room)

Extract mechanical ventilation was switched on throughout the experiments. Supply mechanical ventilation (for both the CR chilled beams and the WR grilles) was switched either on or off depending on the requirements of a specific configuration. CR1 and CR5 doors were both open throughout the experiment and all other doors were closed. VALUATOR was located in one of 4 locations (CR1, CR5, WRA, and WRB). The configurations reported in Table 2 were analyzed with supply mechanical ventilation switched on.

These 4 configurations were then repeated with the supply mechanical ventilation switched off. This entire set of 8 configurations was repeated for VALUATOR in each of the 4 locations (CR1, CR5, WRA, and WRB), for a total of 32 tested configurations.

3. Results

3.1. Particle migration to a neighbouring room

Aerosol spread from CR8 in the presence of mechanical ventilation and various PAC configurations is presented in Figure 2. All baseline levels at the start of each experiment linearly extrapolated over 15 min were at most 0.17% of the cumulative source room particle count (for a maximum extrapolated baseline count of 47,371, equivalent to 1116 particles/l/min). Closing doors significantly reduced aerosol migration

Table 2. 'Cross-Clinic Particle movement' experiment configuration.

Experimental Run	P1 (small) PAC in CR1 and CR5)	P1 (small) PAC at Nurses' Station	P2 (large) PAC in Waiting Room Areas	Supply Mechanical Ventilation	Extract Mechanical Ventilation
1	–	–	–	✓	✓
2	–	–	✓	✓	✓
3	✓	✓	–	✓	✓
4	✓	✓	✓	✓	✓
5	–	–	–	–	✓
6	–	–	✓	–	✓
7	✓	✓	–	–	✓
8	✓	✓	✓	–	✓

Experiments were undertaken using eight different configurations, with portable air cleaners (PAC) and supply mechanical ventilation in consulting rooms (CR), Nurses' station and waiting room areas switched on indicated by '✓') or off (indicated by '–'). extract mechanical ventilation remained on throughout all experiments.

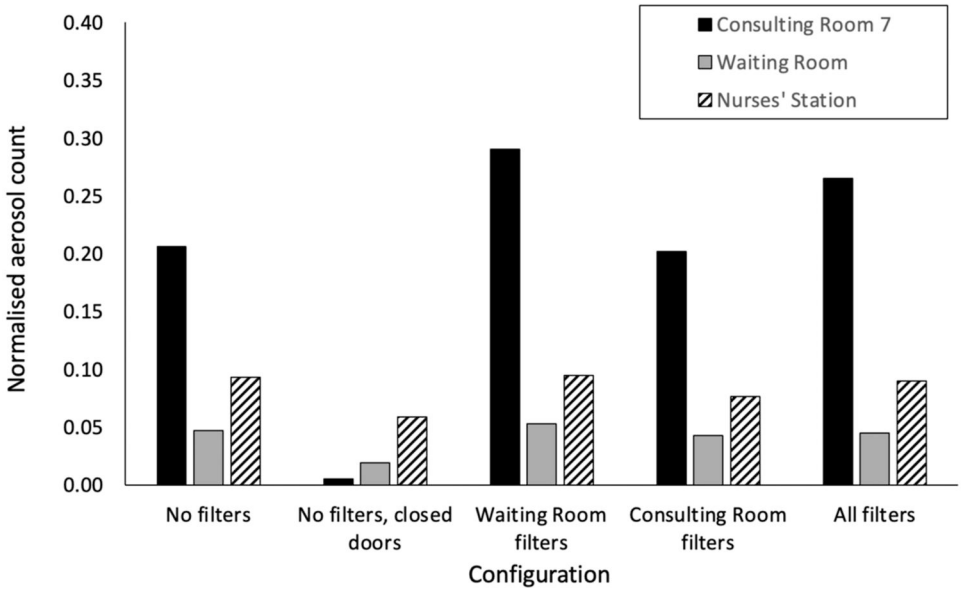

Figure 2. Particle Migration to a Neighboring Room. Results of experiments for particle migration from a consulting room (CR) 8 to CR7, waiting room and Nurses' station. Effect of portable mitigation upon aerosol migration from one CR to a next-door CR and two adjoining communal areas. Cumulative aerosol counts are normalized to that of the source room (CR8) for the first experimental run, when no portable air cleaners were used and CR7 and CR8 doors were open (configuration 1 in Table 1). All mechanical ventilation was switched on throughout and all doors were closed except for doors CR7 and CR8. For this figure, a normalized aerosol count of 1 is equivalent to an aerosol concentration of 1,488,516 particles/l/min.

to neighboring rooms. Counterintuitively, when WR PACs were on, aerosol migration *increased* to all locations. Adding a PAC in each CR and at the nursing station reduced these particle counts slightly, but in the next-door CR (CR7) these measures did not reduce the particle count below the "No Filters" configuration. Particle counts with respect to time for all configurations are presented in the appendices (Figure S3), in order to represent the transient nature of the dispersion.

3.2. Particle migration across full clinic

Aerosol migration from CR5 to all other locations in the clinic in the presence of mechanical ventilation, a PAC in each location, and all clinic room doors open is presented in Figure 3. All baseline levels at the start of each experiment linearly extrapolated over 15 min were at most 3.6% of the cumulative source room particle count (for a maximum extrapolated baseline count of 14,873, equivalent to 350 particles/l/min). These results show that the aerosols are being blown from CR5 across WR B toward CR1 and the nursing station. This appears to be due to the configuration of the air conditioning system in the clinic. Aerosol counts resulting from VALUATOR being placed in the other CRs are presented in the appendices (Figure S4). The transient nature of the particle dispersion into all rooms for this scenario is presented in the appendices (Figure S5).

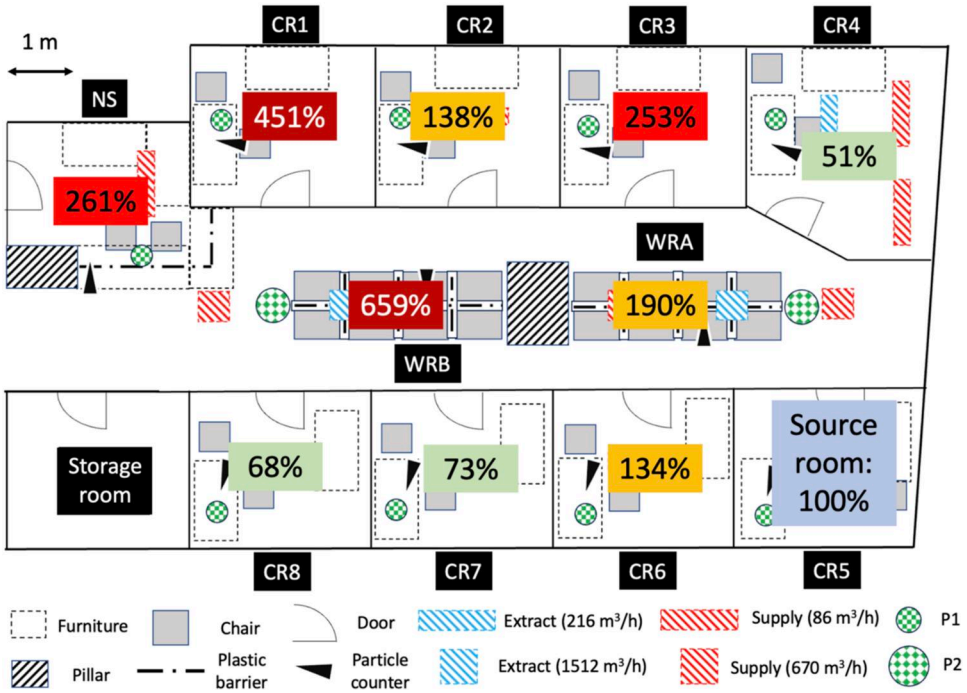

Figure 3. Particle Migration Across Full Clinic. Aerosol migration to all locations resulting from aerosol source in Consulting Room (CR) 5. Cumulative aerosol counts are presented as a percentage value compared to the particle count in CR5, where the aerosol concentration was measured as 9,652 particles/l/min. All mechanical ventilation was switched on throughout, all doors were open, and a portable air cleaner was switched on medium setting in each location. NS: Nurses' Station; CR: Consulting Room; WR: Waiting Room.

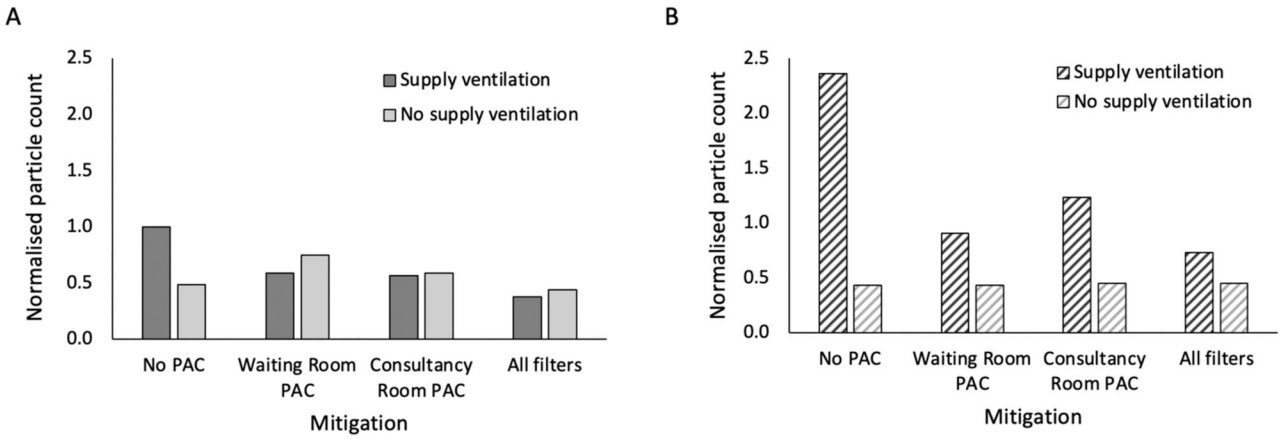

Figure 4. Cross-clinic Particle Movement. (A) Aerosol migration counts for Consulting Room (CR) 1. (B) Aerosol migration counts for Nurses' Station. 'Supply Ventilation' indicates that all supply and extract mechanical ventilation was switched on, 'No Supply Ventilation' indicates that supply mechanical ventilation was switched for both WR and CRs, but extract ventilation remained switched on. All doors were closed, except for CR1 and CR5. CR: Consulting Room. Cumulative aerosol counts are normalized to the count for CR1 with the 'Supply Ventilation, no PAC (Portable Air Cleaner)' configuration, which produced the highest aerosol count in CR-1. For this figure, a normalized aerosol count of 1 is equivalent to an aerosol concentration of 21,113 particles/l/min.

3.3. Cross-clinic particle movement

Aerosol migration from CR5 to CR1 and NS with variations in mechanical ventilation and PAC configuration is presented in Figure 4. Aerosol counts resulting from VALUATOR being placed in CR1, WRB, and WRA are presented in the appendices (Figure S6). All baseline levels at the start of each experiment linearly extrapolated over 15 min were at most 2.4% of the cumulative source room particle count (for a maximum extrapolated baseline count of 33,872, equivalent to 798 particles/l/min). Doors to all CRs except CR5 and CR1 were shut throughout the experiment. With mechanical ventilation switched on, aerosol counts in both CR1 and NS reduced when any

configuration of PA1-4dC was used, with decreases ranging from 41% to 62% for CR1 and 48% to 69% for NS. With supply mechanical ventilation switched off, aerosol migration decreased for all NS aerosol counts in comparison to the equivalent configurations in the presence of supply mechanical ventilation (39%–82% reductions, see Figure 4b). The results for the aerosol counts in CR1 in the absence of supply mechanical ventilation are less clear cut (see Figure 4a) – in the absence of PACs as well as supply mechanical ventilation, the aerosol count decreases 52% compared to the ventilated equivalent. However, when PACs are introduced, whilst the ventilated configurations result in lower aerosol counts, there is an increase of 3%–27% for corresponding non-ventilated configurations, most notably when only WR PACs are used (27% increase). Particle counts with respect to time for all configurations are presented in the appendices (Figure S7), in order to show to the transient nature of the dispersion.

4. Discussion

Aerosol spread across a typical hospital Outpatients clinic was simulated *via* use of a nebulized saline solution and analyzed with particle counters positioned in locations throughout the clinic, with various combinations of mechanical ventilation, PACs, and physical barriers acting as mitigation against the migration of these aerosols.

Figure 2 shows that closing doors to CRs leads to a significant decrease of aerosol migration – 37%–59% lower between neighboring locations when aerosols must pass by one closed door, and 97% lower when a second door is introduced. However, use of PACs to increase air changes (increasing from ∼6 to 8 air changes per hour with open doors and all mitigation turned on in the clinic analyzed) does not lead to a clear-cut relationship between increased PAC usage and decreased aerosol migration. Whilst the use of PACs in the CRs alone led to a migration decrease of 2%–19%, the use of PACs in the WR led to an increase in the non-source CR, and in fact was exacerbated by 29% when PACs were used in the two CRs. This may be due to the creation of air flows in the WR, potentially creating circulations that enhanced aerosol removal from the source room (CR8) and/or migration in the non-source room (CR7). As the extract mechanical ventilation grilles are located in the WR and CR4 and all CRs have supply mechanical ventilation, the CRs are designed to be at positive pressure compared to the WR, and so particles from a source in any CR without extract mechanical ventilation would tend to migrate to the WR. With estimated mechanical ventilation for the clinic of 6 ACH, this trend would be expected to be established quickly – as Figure 2 shows, it seems well established within a short consultation of 15 min. However, deviations from the designed air flow/pressure configuration could lead to air recirculation forming in the relatively large WR volume and air being pushed back into one or more of the CRs, and aerosols building up in that room, as shown in Figure 3.

Whilst PACs will decrease the aerosol concentration in a room once the source has left (Salmonsmith et al. 2023), and have the potential to reduce aerosol concentration during aerosol seeding, it is important to consider the outlet air flow of each of these devices (in this case on the top of the device), as they can evidently push aerosols away from the HEPA filter of the PAC and circulate around or into non-desirable volumes. The optimal Placement and setting of these PACs could be determined/enhanced by the usage of numerical simulations, including computational fluid dynamics analysis (Guo et al. 2021). Interestingly, the cumulative particle counts for NS were always higher than those of the WR, despite the WR being closer to the source CR. This suggests that the aerosols were building up in the NS over the duration of each experiment, whereas the aerosols had more of a tendency to migrate through the WR, continuing on to other areas of the clinic or being extracted through the extract mechanical ventilation grilles in the WR – proximity to the source of the potentially infectious aerosols is not the only risk factor. Although the PACs have an impact upon the particle migration through the clinic, as shown in the experiments detailed in this article, the movement is expected to be dominated by the underlying mechanical ventilation design. The variability of the aerosol migration when originating from different CRs indicates that a particular ventilation and PAC setup can influence aerosol movements from different sources to very different extents.

When all CR doors were opened, and the subsequent migration of aerosols in the presence of PACs and mechanical supply/extract ventilation was analyzed it revealed that the air currents in a volume can be complicated, and lead to potentially unexpected results. In the case presented in Figure 3, where VALUATOR was placed in CR5, the highest cumulative aerosol concentrations over the 15-minute analysis period were found to be in the rooms and areas furthest from this. The aerosol concentration in WR B

was 247% higher than area A, despite the latter being immediately next to the source room. Similarly, the aerosol concentration in CR1, the furthest CR from CR5, was 184% higher than the mean aerosol concentration for the CR, with CR4, directly opposite CR5, was 68% lower than this mean.

The mean normalized aerosol count for all locations was 2.16 ± 1.88 and for all CRs was 1.59 ± 1.34. CR1, the furthest CR from the source, had the highest migration of aerosols of the CR, 184% higher than the mean aerosol movement to a CR. CR4, the room directly opposite CR5, had the lowest aerosol migration, 68% lower than the mean aerosol migration to a CR. WRA had a 247% higher aerosol count than WRB, although it was the further of the two WR locations. The NS had a higher aerosol count than any of the CRs on the same side of the clinic as the source (CR5-8), 28% higher than the average aerosol count for all clinic locations. This again shows that the usage of mechanical ventilation and PACs can create unfavorable and unexpected air flow patterns that lead to a build-up of potentially infectious particles in volumes that may be relatively far from the source of these particles, whilst other regions much closer to the source may be relatively shielded from these same aerosols.

Further investigation into the migration of particles between CR1 and CR5 and the intervening WR areas when altering the airflow mitigations available (mechanical ventilation and PACs) showed that the complication of increasing air changes per hour upon aerosol migration is not limited to PACs. In the absence of PACs, switching off the supply mechanical ventilation led to a decrease in particle movement from CR5 to CR1 and NS, of up to 82%. This is most likely a result of significantly decreasing the air flow in the region, reducing the migration of aerosols from one side of the clinic to the other, but demonstrates that increasing air changes per hour by using mechanical ventilation (in this scenario, mechanical ventilation provided around 8.8 ACH, and PACs 1.3 ACH) does not necessarily prevent/reduce aerosol migration. Indeed, it may also lead to increased migration of potentially infectious aerosols to some relatively distant regions of an indoor space, due to the added airflow propulsion of the mechanical ventilation. The use of PACs alongside mechanical ventilation led to decreases in CR1 and NS, ranging between 41-69% reductions, but the use of PACs in the absence of mechanical ventilation could sometimes lead to increases of aerosol concentration, particularly when the large PACs were used in the WR. It is possible that the outlet air flow from these machines provides the WR volume with a sufficient air current (otherwise lacking in the absence of supply mechanical ventilation) to enhance aerosol migration from one side of the clinic to the other. Again, although increasing the airflow through an indoor space may decrease aerosol migration overall and for specific regions within that indoor space, there is also the potential for the resultant complex increased air currents to enhance aerosol migration to other certain nearby locations that previously may have been relatively unscathed by potentially infectious aerosols. Comparing the particle build-up in CR1 from this "Cross-Clinic Particle Movement" investigation (where the doors to CRs 2–4 and CR6–8 were all shut) to the build-up recorded in the "Particle Migration Across Full Clinic" investigation suggests that the additional PACs and mechanical ventilation active in all the CRs in the "Particle Migration Across Full Clinic" experiment contribute to increasing the airflow rate from CR5 to CR1, leading to a higher migration of aerosols to CR1, despite there being an increased ACH in the clinic as a whole. The complex air flows within this real-world environment of the hospital clinic show that introducing devices and mechanisms to improve overall ACH can have unexpected and concerning alterations to aerosol migration, increasing the risk of people within a clinic location from an infectious source of aerosols in another relatively remote location in the same clinic.

This research shows that, when increasing the airflow of a region to mitigate the risk of infectious airborne viruses, careful consideration of the resultant airflows and aerosols' path lines is required. Work by Buising et al. (Buising et al. 2022) indicated that despite exceeding recommended mechanical ventilation airflow rates, the use of this mitigation alone did not adequately clear artificially generated aerosols in a timely manner. Our study indicates that whilst chilled beams achieve recommended designed airflow rates and may provide effective mitigation in some scenarios, the resultant air flow dynamics may not be optimal for all situations. Machine-powered air flow can propel aerosols to relatively distant locations of indoor spaces, increasing exposure of potentially infectious particles to residents. The work by Edwards et al. (Edwards et al. 2024) suggests that use of natural ventilation, such as an open window, produces airflow patterns that are also difficult to predict. Accordingly, whether natural or built-in mechanical ventilation is used, there may some regions of hospital clinics that suffer from an increased build-up of potentially

infectious aerosols than other regions, in a manner that may not be straight-forward to predict.

The development of predictive numerical simulations may increase the ability to assess the flow dynamics of a clinic for different combinations of mechanical ventilation and PACs, giving confidence that the deployment of mechanical ventilation and air cleaning devices are having the intended effect. Even relatively simple and seemingly effective strategies, such as closing doors, do not protect all regions equally, as can be seen by the relatively high aerosol concentration in the NS when all doors are closed, as aerosols, unable to easily enter into CRs due to barriers, gather in NS situated at the end of the WR. It is important to note that it is hard to generalize these specific findings to other healthcare designs, where the mechanical ventilation, PAC layout, and room layout is likely to be different. Further investigation of these variables and their effect upon particle migration and air flows is needed.

The ideal solution would not just increase the rate of airflow, but would also optimize the path that air takes within an indoor space. Taking air flow dynamics into consideration when designing or retrofitting medical healthcare spaces would provide more cost-, energy-, and time-efficient results than overly focussing on airflow rate as the primary ventilation factor. Using PACs may well be a viable option, but it is important to consider the impact on the air flow path when placing these devices. Future work could include the investigation of using multiple small PACs rather than fewer large units, to avoid creating strong air flows that may transport aerosols over long distances. The use of computational simulations using CFD would be important in validating the findings from this work, and extending the analysis to establish ideal positioning and use of mitigations such as PACs.

4.1. Limitations

To reduce the variability of these experiments, they were carried with no staff or patients walking around the clinic, and with no doors opened or closed during a run. Although this makes the results easier to interpret and apply, the movement of people and doors will also alter the air flow patterns in an indoor space and should be taken into account with future work. Droplet size distribution, humidity, and temperature were not prioritized in this work, instead concentrating on migration characteristics of the aerosols. The use of more physiologically accurate saliva surrogates might have produced aerosols closer to the size distributions contained in human exhalation than the use of saline (De Oliveira et al. 2021). VALUATOR did not produce droplets in a pulsatile fashion similar to human breathing, but instead expelled a constant stream of aerosols, simulating an extreme scenario of aerosol production. The use of cumulative particle counts over a 15-minute period measured from one position within each area of interest could be improved by using multiple particle counters in each area of interest, generating a more nuanced analysis of each area and enabling a more in-depth characterization of the aerosol migration patterns for each scenario.

5. Conclusions

This research shows that although the introduction of PAC devices reduce the aerosol concentration of the space they are placed in for most cases, they may also have unintended effects upon aerosol migration. The positioning of PACs across a clinic may result in increased aerosol migration from some areas to other areas of the clinic, potentially increasing transmission risk of infectious airborne pathogens. For example, when PACs and built-in mechanical ventilation were both in use, the aerosol concentration in one part of a WR was 247% higher than a neighboring area of the WR, despite the latter being immediately next to the source of the aerosols. However, the same PAC and mechanical ventilation setup also resulted in significantly reduced aerosol migration when the source was in another CR, by up to 96%. These contrasting results show how the usage and deployment of built-in mechanical ventilation and PAC needs to be very carefully mapped out, with increased capacity being only one factor in this. The development of predictive numerical simulations may increase the ability to do this, giving confidence that the deployment of mechanical ventilation and air cleaning devices are having the intended effect.

Initialisms

ACH	Air Changes per Hour
AHU	Air Handling Unit
CADR	Clean Air Delivery Rate
CR	Consulting Room
NS	Nurses' Station
PAC	Portable Air Cleaner
PC	Particle Counter
WR	Waiting Room

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