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Matharu, R.K. orcid.org/0000-0003-3687-5119, Hoch, G., Bhatti, M. et al. (2 more authors) (2025) Efficacy of ventilation strategies and plastic partitions in mitigating the spread of aerosols in indoor spaces. Building and Environment. 113342. ISSN 0360-1323

https://doi.org/10.1016/j.buildenv.2025.113342

Efficacy of Ventilation Strategies and Plastic Partitions in Mitigating the Spread of Aerosols in Indoor Spaces

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Abstract

During the COVID-19 pandemic, protective physical barriers and ventilation strategies, were used to prevent the rapid multi-directional exchange of bio-aerosols that occur when people interact in close proximity. Physical barriers provided a cheap solution that was rolled out in many spaces, yet there is little definitive proof of their impact on aerosol transport and infection risk. This study considers the impact of ventilation (no ventilation/5 air changes per hour(ac/h)), air movement strategies (mixing/no mixing) and room partitions (50 cm^2, 125 cm^2, 210 cm^2) on aerosol concentration, size distribution, and deposition. The results show 5 ac/h leads to a reduction in all particle sizes, ranging from a 20 % reduction for 0.3 µm particles to 38 % for 3 µm particle counts. The addition of air mixing to 5 ac/h resulted in higher reductions (from 38 % for 0.3 µm to 88 % in 3 µm) when compared to no ventilation. In the absence of ventilation, the small partition had the greatest impact on aerosol reductions, from 7 % for 0.3 µm to 33 % for 3 µm. At 5 ac/h, the large partition was most effective with reductions ranging from 30 % for 0.3 µm to 24 % for 3 µm aerosols. Once air mixing was introduced, the impact of partitions was minimised due to air homogenisation. The results suggest good ventilation outweighs the impact of partitions in indoor spaces, however in the absence of ventilation, small and large partitions reduce aerosol numbers and subsequently transmission risk.

Keywords: bio-aerosols; droplets; aerosols; infection prevention; ventilation; partition screen.

1.0 Introduction

Diseases, such as tuberculosis, chickenpox and acute respiratory syndrome coronavirus (SARS-CoV) are examples of infectious diseases transmitted via the airborne route. They are caused by pathogenic microbes that are released into the air via respiratory droplets or aerosols of an infected individual or source [1]. These particles are typically discharged during activities such as coughing, sneezing, talking, singing, breathing or any respiratory activity. At present, the World Health Organisation (WHO) and Centers for Disease Control and Prevention (CDC), both define droplets as having a diameter of ≥5 µm, while aerosols have a diameter <5 µm [2,3]. However, both can be generated as a continuum of particle sizes during numerous activities and their behaviours are not distinct. Droplets of all sizes may settle over periods of time to contaminate a variety of surfaces subsequently spreading to those who may use or touch them, particularly if they are in contact with the face. On the other hand, smaller aerosols remain suspended within the turbulent gas cloud, extending their range to reach the heights of the ventilation systems, and can cause infection when inhaled [4,5,6].

Both aerosols and droplets can carry pathogens, thus subsequently facilitating respiratory disease transmission. The infectious dose of pathogenic microorganisms contained within an aerosol or droplet greatly differs, depending on the generation mechanism and aerosol/droplet size. For example, the number of pathogens in fine droplets has been measured to be larger than that in coarse droplets [10]. Lindsley *et al*. reported that in the droplets produced by coughing, 35% of influenza RNA was contained in particles more than 4 µm in aerodynamic diameter, while 23% of RNA was contained in particles 1 to 4 µm and 42% RNA in particles <1 µm [10].

During normal respiration, the majority of droplets produced are smaller than 0.3 µm in aerodynamic diameter, with a minority (less than 2%) being larger than 1 µm [8,9]. In contrast, during coughing, the majority of droplets produced are 13.5 µm in aerodynamic diameter, whilst during speaking, droplets are slightly larger at 16.0 µm [8,9]. Chao *et al*. have also reported that the number of droplets exhaled during speech was much less compared to violent exhalations such as sneezing and coughing [9].

To minimise aerosol and droplet transmission, ventilation, personal protective equipment (PPE) and physical distancing have been highlighted as effective interventions. The physical distance between people is suggested as at least 1 m by the WHO [10]. However, a distance of 2 m or more is far more effective, as the recommended distances do not take into consideration the possibility of aerosols being conveyed by a high momentum cloud [4]. In scenarios where it is not feasible to keep an adequate physical distance or wear PPE, the WHO recommends installing separate and transparent physical dividers [11]. It is thought placing dividers in between two interacting people can reduce the risk of infection caused by aerosol/droplet transmission. Although numerical simulations of air flow have been used to evaluate the performance of dividers, little experimental evidence exists.

In a study by Li *et al*., the movement of aerosols/droplets emitted from an infector during a cough was simulated and it was found that a desk divider effectively protected and reduced the inhaled dose of an exposed person seated face-to-face 1.5 m away [12]. It was also found that displacement ventilation reduces the inhaled infectious dose by a receptor. In a study by Liu *et al*., the impact of dividers in dining areas was explored using computational fluid dynamics (CFD) [13]. The dividers showed limited effects on blocking the path of long-distance aerosol transmission. Instead, the aerosols gathered in the breathing zone inside the partitioned space, consequently putting the next diner at risk of infection [14]. This demonstrates how physical dividers run the risk of creating stagnant or recirculating flow, resulting in the accumulation of pathogenic microorganisms close to the source. In a CFD study by Cheong and Lee, physical dividers between hospital beds were shown to generally reduce the average concentration of airborne pathogens, while increasing the concentration at the beds opposite and adjacent to the source [15]. The most effective method for preventing pathogen dispersion and reducing pathogen concentration was found to be increasing the ventilation rate [12,15,16,17].

Most of the existing studies on the effects of physical dividers and ventilation on airborne transmission use CFD simulations [18,19,20,21,22], while there is limited experimental work to complement this [23,24]. The few studies that do exist, focus on specific scenarios or

simplify the aerosol transmission to a behaviour of a gas, ignoring any changes in deposition [25]. Ching *et al.* found that the use of hospital curtains could reduce the peak concentration of bioaerosol dispersion in CFD simulations [26]. In another experimentally validated simulation study, Ren *et al*. found that barriers of a height of at least 60 cm were needed to reduce bioaerosol concentration [21]. More recently, Traversari *et al*. carried out an experimental study which showed that effective ventilation was more effective than social distancing in a restaurant mock up [27]. They also considered different mocks ups of the restaurant with a mix of different screen sizes in each scenario. Two of the mock ups with screens showed a significant decrease in exposure, however one did not. Another experimental study by Li *et al.* found that partitions were effective at reducing the aerosol cloud in the face-to-face configuration, though ventilation was not used as a parameter in the experiments [28]. Zhang *et al*. considered a range of face-coverings and barriers, showing a reduction in exposure at short distances with the presence of a barrier [25]. However, they highlight the impact of the ventilation system design on the protective performance of the barrier. In an intervention study, Gettings *et al.* reported a 37 % lower incidence of COVID-19 in school that required teachers to use masks and 39 % lower in schools that improved ventilation [29].

Li *et al.* and Zhang *et al.* are the two studies of partitions that consider generic scenarios and could be applied to consideration of face-to-face scenarios such as shops and reception counters [25,28] Li *et al.* considered changes to partition layout but not size, and did not consider the impact of changing ventilation [28]. Zhang *et al*. considered changes to ventilation strategies with two sizes of partition [25]. However, they didn't consider scenarios with no ventilation (which unfortunately exist in real life), and the experiments were carried out with a gas rather than an artificial saliva solution. This prevented consideration of the transport and deposition of larger droplets which may be generated during coughing and sneezing. We are not aware of any experimental study that has investigated the role of ventilation / no ventilation and partition size with analysis of both airborne counts and deposition allowing for consideration of infection transfer to hands and through inhalation. In order to provide recommendations for use of screens in future pandemics it is essential that experiments are carried out in both poorly and well ventilated environments. To consider the range of possible infection routes experments need to consider the impact of the screen on both airborne particle counts, and deposited particles.

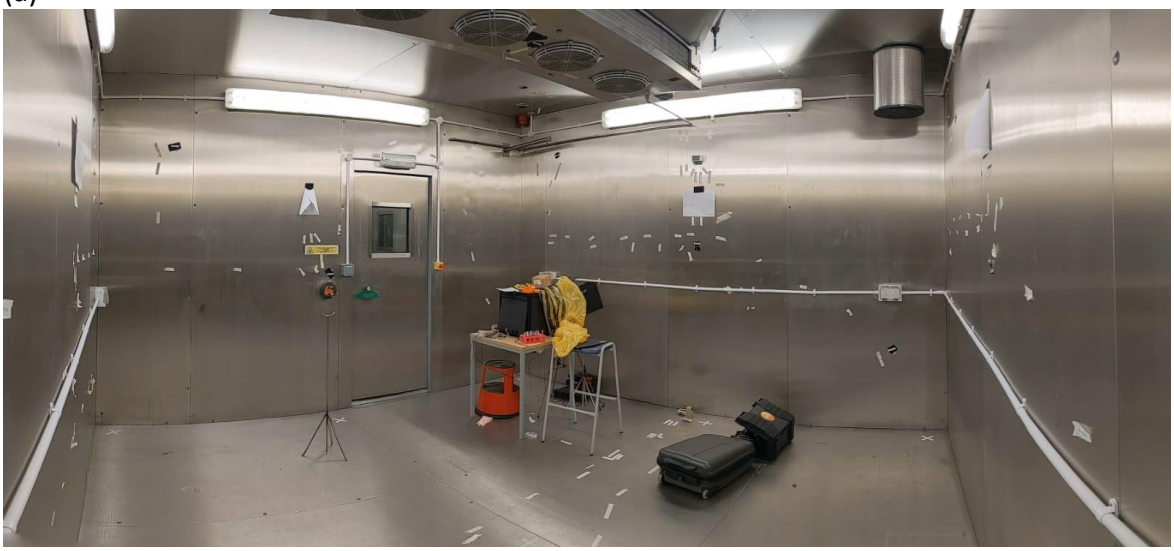
The objective of this study was to address this gap by using a controlled test chamber to assess the relative effects of physical dividers and ventilation strategies on the movement, removal and deposition of airborne particles from source to receptor. The scenarios, with the source facing receptor, are particularly relevant for scenarios with retail or reception desks where a screen is between customer and staff. The study used aerolised artificial saliva to investigate, (i) the airborne dynamics as saliva evaporates to a droplet nuclei and (ii) to quantify the changes in deposition alongside airborne counts. Importantly the study compares the impact of physical dividers under a range of ventilation regimes, including that of no ventilation.

2.0 Materials and Methods

In this work, the effect of different ventilation strategies and physical dividers on the movement of aerosols were investigated over a time period of 100 minutes. All work was conducted in a Biosafety Level 2 Walk-In Environmental Chamber (Unitemp LTD, Buckinghamshire, U.K.) (**Figure 1**), where room conditions were set to 20^{o}C and 50% RH - as

these are considered comfortable conditions for human occupancy (CIBSE 2021). The chamber's width and length were 4 m by 4 m with a height of 2.8 m. All experiments were carried out in triplicate, unless stated otherwise.

(a)



(b)

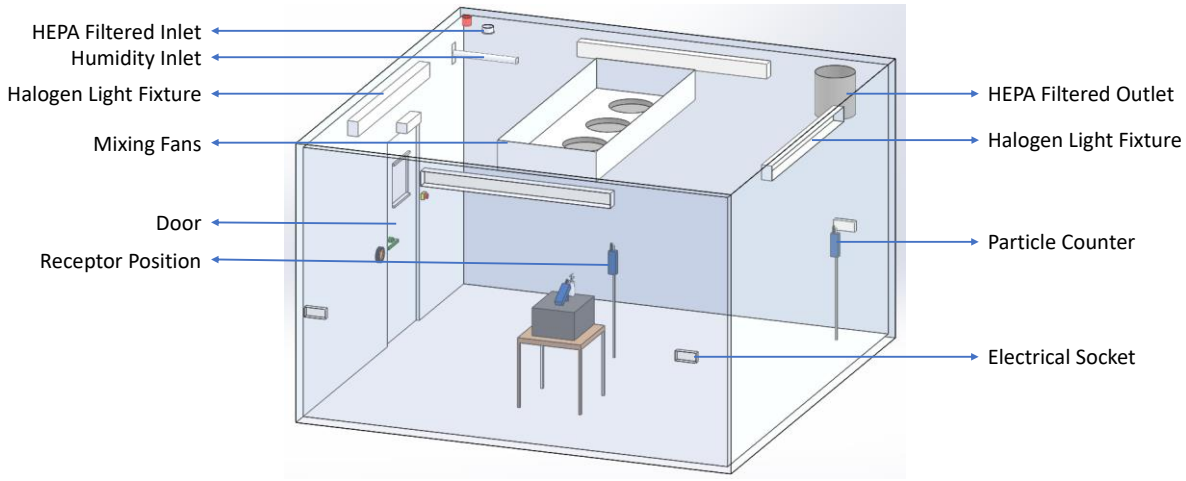


Figure 1: (a) image of the chamber; (b) CAD model of the chamber.

A 6 Jet Collison Nebuliser (ACOEM UK LTD, Tewkesbury, U.K.) was used to aerosolise artificial saliva (product code SAE0149 purchased from Sigma Aldrich, Dorset, U.K.). Compressed air was supplied to the nebuliser at a pressure of 20 psig to achieve a flow rate of 12.5 l/min. This produces aerosols with a mass median diameter of 2.5 and a geometric standard deviation of 1.8 [31].

Particle counts were recorded every 60 seconds for the duration of the experiment using a TSI AeroTrak® Handheld Particle Counter Model 9306, in 3 separate locations (as shown in **Figure 1b** and **Figure 3**). All counters recorded particle counts in the following channels: 0.3 – 0.5 µm, 0.5 – 1.0 µm, 1.0 – 3.0 µm, 3.0 – 5.0 µm and 5.0 – 10 µm, as well as logging temperature and humidity. The sampler was calibrated in accordance with ISO 21501:4 prior to use.

Counter 1 was positioned 10 cm behind the nebuliser outlet; this provided information on the particle counts close to the source. Counter 2 was placed 1 m away from the nebuliser outlet, thus providing information from a receptors position. All counter heights were the same as the nebuliser outlet – 115 cm from the floor.

The chamber was conditioned to 20°C and 50% RH, before being allowed to rest for 30 minutes prior to starting each experiment to ensure no external movement caused turbulence in the chamber. After 30 minutes, the particle counters began recording, 10 minutes into this, the nebuliser was turned on and allowed to run for 60 minutes, after which it was turned off and the experiment ended (**Figure 2**). Particle counts were collected for 10 minutes prior to initialising the nebuliser to check background counts and continued to be measured until nebulisation stopped. Particle counts for analysis were taken after the nebuliser had been running for 30mins until the end of the experiment. The chamber underwent 5 complete air changes between each experiment: if the space is fully mixed this would result in the removal of 99.3% of aerosols. Background counts at the receptor prior to nebulisation were below 5% of experimental sample used for analysis in the scenarios where ventilation was switched on. In the scenario with no ventilation the background counts at the receptor were below 10% of the experimental samples used in the analysis.

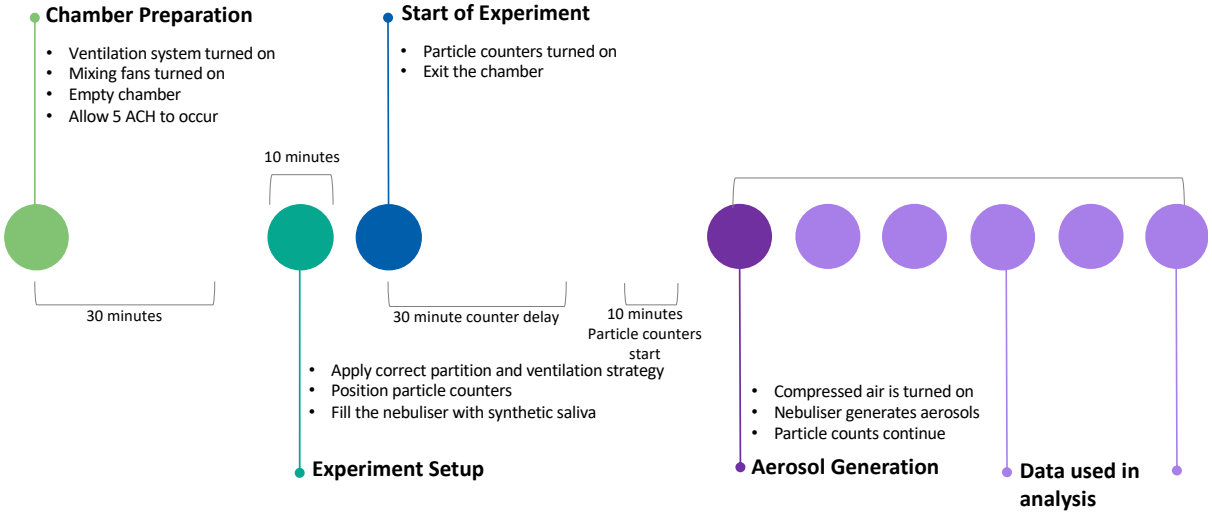


Figure 2: experiment timeline.

2.1 Ventilation Strategies

The following ventilation conditions were employed: (i) sealed chamber with no outdoor air supply or room conditioning; (ii) HEPA filtered outdoor air supplied at 5 air changes per hour (ac/h), removed via a passive extract (no diffusers on inlet, and no internal mixing fans. This resulted in some short circuiting of room air flow and internal room air speeds averaging 0.29 m/s (ranging between 0.10 and 2.43 m/s)); (iii) HEPA filtered outdoor air supplied at 5 ac/h and room conditioned via a recirculation system located in the centre of the ceiling (**Figure 1b**). The recirculation system consists of 4 mixing fans running at an average speed of 3.55 m/s, resulting in average air speeds of 0.61 m/s in the room (ranging between 0.26 and 2.53 m/s). The only additional heat source except the climate control system in the chamber was from the particle counter which would be negligible. The lights remained off during the experiments.

2.2 Physical Dividers

All partitions were made from 5 mm thick acrylic. The partitions were held upright using a timber frame and were attached to the frame using metal brackets and screws. The partitions were placed in the centre of the chamber and 50 cm away from the nebuliser outlet. The centre of the partition aligned with the outlet of the nebuliser. Exact dimensions and partition placement are provided in **Table 1**.

Table 1: summary of partition strategies tested, including physical divider size and placement.

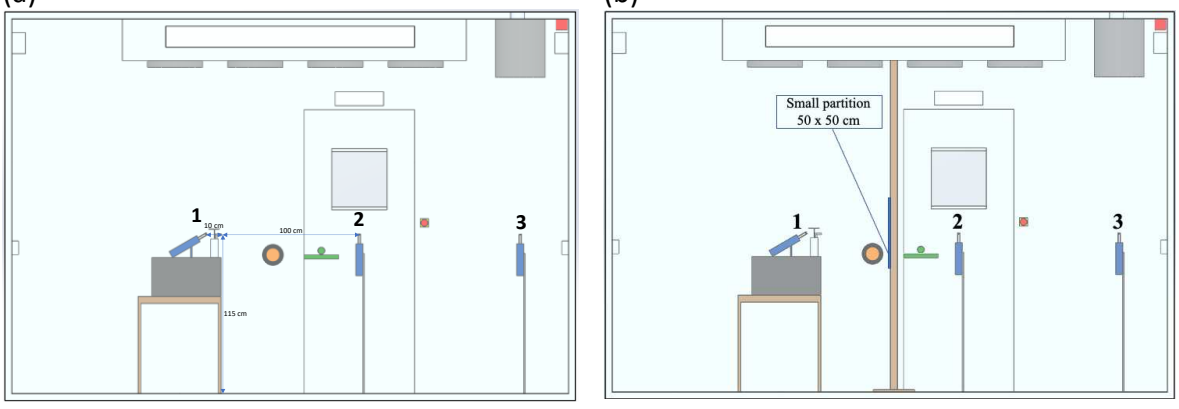
Partition Strategy	**Size and placement**
Control – no partition	-
Small	50 cm by 50 cm; installed 90 cm from the floor
Medium	125 cm by 125 cm; installed 52.5 cm from the floor
Large	210 cm by 210 cm; placed directly on the floor

In this work the effect of different ventilation strategies combined with the use of four partition strategies were investigated (summarised in **Table 2** and shown in **Figure 3**). For each combination, three runs were conducted.

Table 2: ventilation and partition strategies tested.

Partition Strategy	**5 Air Changes**	**Mixing Fans**
Control – no partition	Off	Off
	On	Off
	On	On
Small	Off	Off
	On	Off
	On	On
Medium	Off	Off
	On	Off
	On	On
Large	Off	Off
	On	Off
	On	On

(a) (b)



(c) (d)

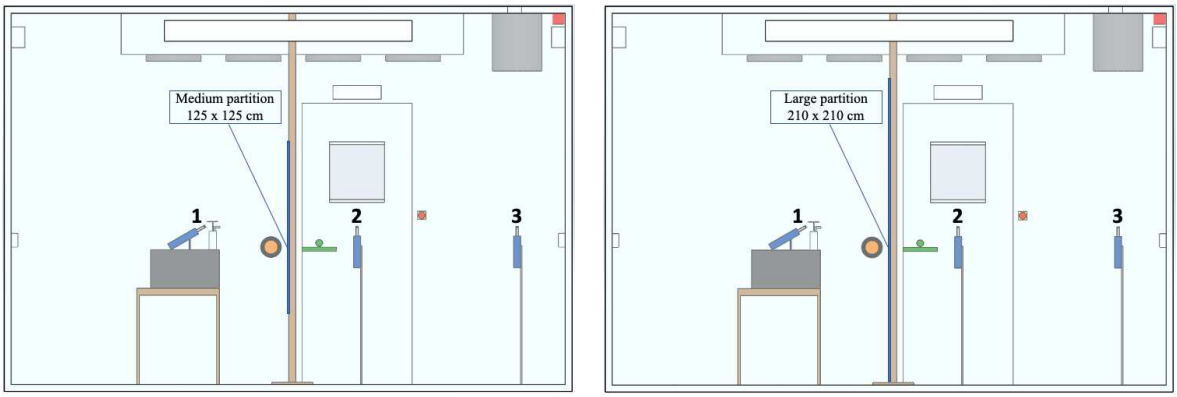


Figure 3: CAD drawings of the experimental set up: (a) control; (b) small partition; (c) medium partition; (d) large partition.

2.3 Deposition Studies

In this work, aerosol deposition studies were also caried out to determine how partition strategies effect aerosol deposition. The environmental conditions in the chamber were set to 20°C, 50% RH, 5 ac/h and with no mixing fans.

For these studies, a small section the cauliflower mosaic virus (CaMV), a plant pararetrovirus, genome sequence was used. CaMV DNA was chosen as this virus, which poses no risk to humans, and its DNA have previously been used to track transmission in healthcare environment settings [32,33,34]. Using a fragment of known DNA sequence allows for its detection and accurate quantification on surfaces and in air samples using polymerase chain reaction.

A 400 base pair (bp) sequence was selected from the virus and the oligonucleotide synthesised by Integrated DNA Technologies IDT (Leuven, Belgium), sequences shown in **Table 3**.

Table 1: sequence of the synthesised oligonucleotide used as a marker in the deposition studies, with primer pair, amplicon size and highlighted annealing sites.

Sequence (400 BP)	**Forward Primer**	**Reverse Primer**	**Amplicon Size**
ACATGTACAAGACGGAACTGGCGGATTTCCCAGGATATAT CAACCAGTACCTGTCAAAAATTCCCATCATTGGAGAAAAA GCGCTAACACGCTTTAGACATGAAGCCAATGGAACCAGC ATCTACAGCTTAGGTTTTGCGGCGAAGATAGTCAAAGAAG AACTATCTAAAATCTGCGACTTATCCAAGAAGCAGAAGAA GTTGAAGAAATTCAACAAGAAGTGCTGTAGCATCGGAGA AGCTTCAGTAGAATATGGATGCAAGAAGACATCCAAGAA GAAGTATCATAAAAGATACAAGAAAAAATATAAGGCTTATA AACCTTATAAGAAGAAGAAGAAATTCCGATCCGGAAAATA CTTCAAGCCCAAAGAAAAGAAAGGCTCAAAGCAAAAGTA TTG	TGTACAAGACGG AACTGGCCG	TGAGCCTTTCTTT TCTT TGGGC	383

To prevent DNA degradation the oligonucleotide fragment was inserted into a plasmid vector. The pGEM®-T Easy Vector system was used in accordance with the manufacturer's instructions (insertion site shown in **Figure 4**). The plasmid containing the CaMV insert was

subsequently transformed into *Escherichia coli* JM109 High Efficiency Competent Cells according to manufacturer's instructions to allow for propagation of the plasmid.

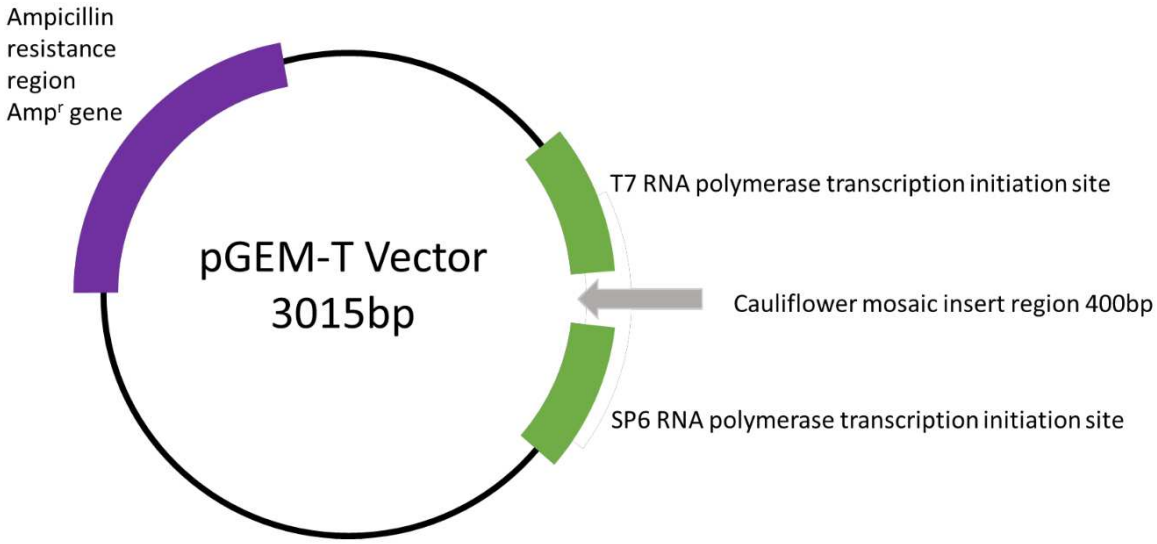


Figure 4: pGEM-T Easy Vector with sequence reference points and insertion region.

Plasmid DNA was then prepared from *E. coli* cells using the QIAGEN Mini Plasmid Purification Kit, according to the manufacturer's instructions. The resulting plasmid DNA was adjusted to achieve an absolute concentration of 10^9 copies in 20 mL of synthetic saliva.

To quantify deposition of the CaMV DNA, 10 mm by 10 mm plastic coupons made from 5 mm thick acrylic were placed in marked positions in the chamber as described in **Figure 5**. Synthetic saliva containing the CaMV DNA was then aerosolised in the chamber using a 6 Jet Collison Nebuliser for 20 minutes. After aerosolization, the chamber was allowed to rest for 30 minutes. Each coupon was then placed in 12 mL of molecular grade water (Corning, Flintshire, U.K.) and sonicated for 5 minutes at maximum intensity (Fisherbrand™ 112xx Series Advanced Ultrasonic Cleaner). 10 mL of this liquid was concentrated, using Vivaspin concentrators, (Sartorius, Epsom, U.K.) to a total concentrated volume of 1 mL. Approximately 200 µL of this was stored in Eppendorf tubes as aliquots.

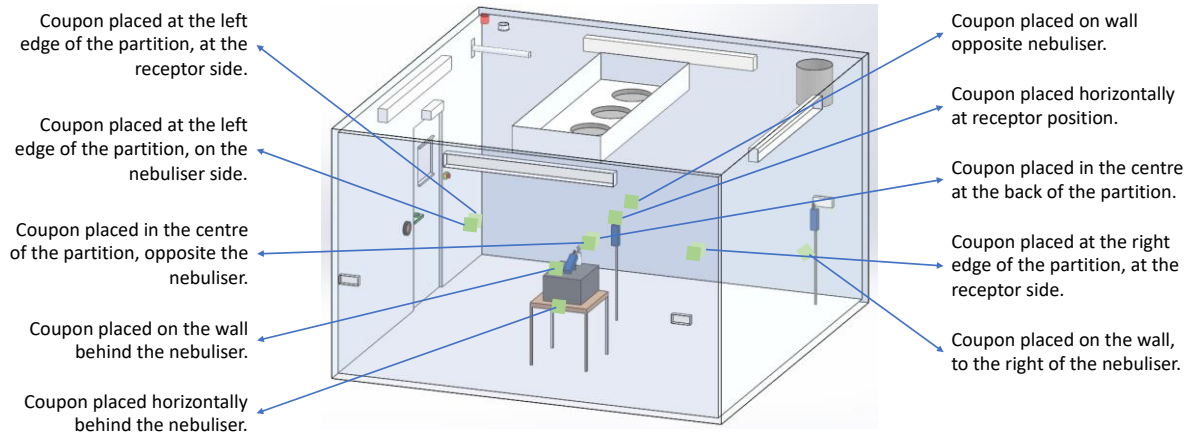


Figure 5: schematic diagram depicting the location of each coupon used for the deposition studies.

Detection of CaMV DNA by real time quantitative polymerase chain reaction (qPCR) was performed using the micPCR system (Biomolecular systems, Australia). 0.5 µL (stock solution at 10 µmol) of CaMV forward and reverse primers, along with 10 µL of Luna® Universal qPCR Master Mix (New England Biolabs,) was added to 9 µL of sample. qPCR cycling conditions were as follows: 95^{o}C for 10 minutes, followed by 40 cycles of 95^{o}C for 15 seconds, 58^{o}C for 15 seconds and 72^{o}C for 15 seconds.

2.4 Data and Statistical Analysis

The data gathered during the last 30 minutes of aerosolization in all experiments were presented as box and whisker plots showing the full range including outliers, quartiles, mean and median. For each scenario this includes 30 samples per experiment repeated 3 times. All graphs were drawn using Excel. The data were analysed using the Repeated Measures ANOVA test on SPSS Statistics 28.0 (IBM Technology Corporation, New York, U.S.) using the full range for each data set. If the data set was not normal, a nonparametric Repeated Measure was performed using the Friedman Test.

3.0. Results and Discussion

3.1. Ventilation significantly impacted concentrations of all particle sizes

Figure 6 compares the effect of three different ventilation strategies (without the use of partitions) investigated in this work. These results showed that the introduction of 5 ac/h resulted in a reduction of all airborne particles. Reductions ranged from a 20% reduction for airborne particles 0.3 – 0.5 µm, to 53% for airborne particles between 5.0 – 10.0 µm, when compared to no ventilation. The addition of air mixing to 5 ac/h resulted in an even higher reduction in airborne particles at the sampling point, with reductions ranging from 39% for airborne particles 0.3 – 0.5 µm to 93% for airborne particles 5.0 - 10 µm, when compared to no ventilation.

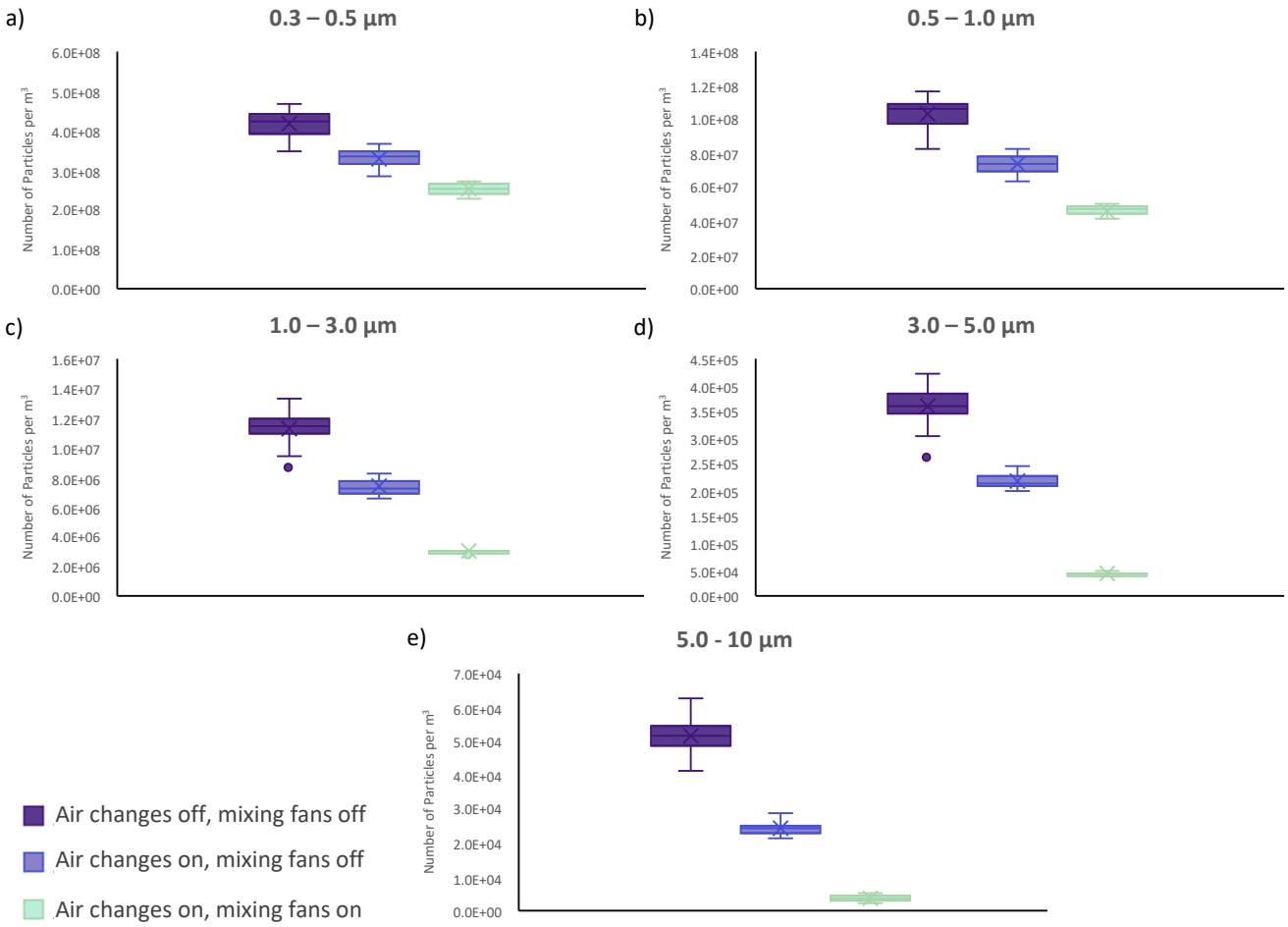


Figure 6: Particle counts collected at counter 2 under different ventilation strategies (no partition). a) 0.3-0.5 µm particles, b) 0.5-1 µm particles, c) 1-3 µm particles, d) 3-5 µm particles, e) 5- 10 µm particles.

The benefits of ventilation for reducing indoor pollutant concentrations are well known [13, 35,36]. In these experiments the expected increased removal of particles is clear with the addition of 5 ac/h, with further reduction due to dilution resulting from the addition of a mixing unit. This directly reduces the exposure of the receptor to potentially infectious material in the air, provides a useful benchmark to compare the performance of partitions to. The mixing unit enables removal due to greater deposition (both in the unit and within the room due to higher air speeds) [37] and ensures good mixing within the room enabling more efficient removal of airborne particles via the 5 ac/h ventilation.

3.2. Impact of partitions is dependent on the partition size and ventilation strategy

Partitions resulted in a reduction of the larger particles with no ventilation (reducing particles > 3µm) and ventilation with no mixing (reducing particles > 5µm). Once a high level of mixing is used then no clear impact from the partitions is observed. Overall, the impact of partitions is minimal in comparison to ventilation strategies.

3.2.1. Partitions with no-ventilation (Air Changes Off and Mixing Off)

Figure 7 compares the effect of various partition sizes, when no ventilation strategy is used (ac/h off and mixing fans off). The use of any partition results in a reduction up to 33% in particle numbers over 3 µm. However, for the smaller particle sizes the results are more variable. The results show that the use of a small partition has the largest reduction of all airborne particles at counter 2 (the receptor position). Reductions for the small partition ranged from 7 % for airborne particles 0.3 – 0.5 µm to 33 % for 5 - 10 µm. The medium and large partitions did not exhibit the same behaviour. The mean particle counts at the receptor for the medium partition is consistently higher than the small partition. Previous studies have not considered the performance of partitions where there is no ventilation. This work demonstrates the benefit of partitions in removing larger particles in an unventilated environment.

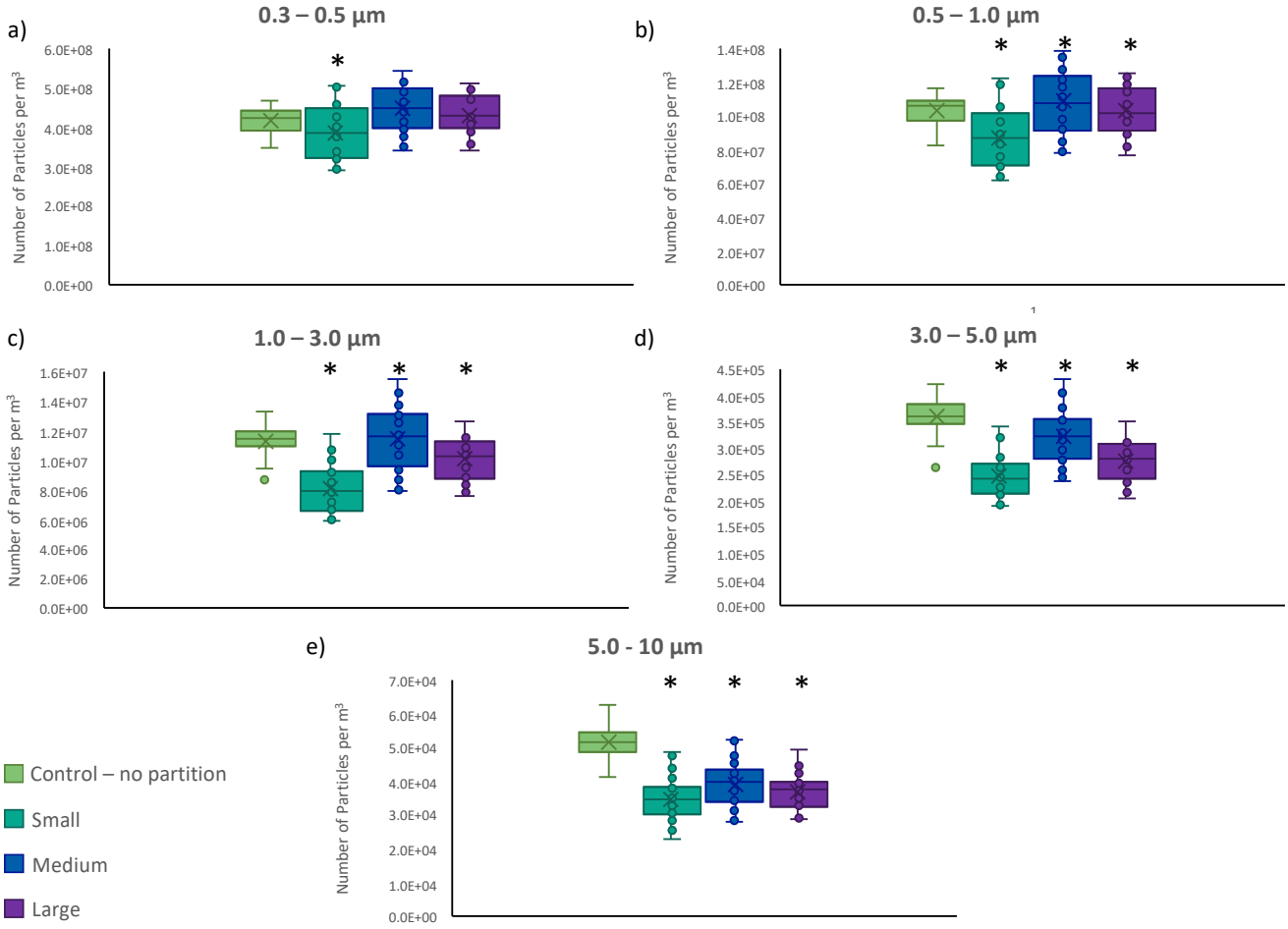


Figure 7: particle counts collected at counter 2 with various partitions in combination with air changes off and mixing fans off. a) 0.3 – 0.5 µm particles, b) 0.5 -1 µm particles, c) 1-3 µm particles, d) 3-5 µm particles, e) 5-10 µm particles. Control, small, medium, and large represent partition strategies. p values of < 0.05 (*) are shown on the graph.

3.2.2. Partitions with un-mixed ventilation (Air Changes On and Mixing Off)

Figure 8 compares the effect of various partition sizes, when 5 ac/h and no mixing were employed. In this case it is only the airborne particles greater than 5 µm that are consistently reduced with the addition of any partition size. With the introduction of 5 ac/h, it can be seen that the large partition was the most effective in reducing airborne particles, with reductions ranging from 24% for airborne particles 5 – 10 µm to 32% for airborne particles between 0.5 – 1.0 µm. Although, this difference is not statistically significant. The medium partition only showed reductions in the largest particle sizes (5-10 µm) and resulted in increased particles at the receptor for some of the smaller sizes.

In this scenario the ventilation is not well mixed, and the effect of the partition varies depending on the interactions between the air flow and the partition. This scenario results in short circuiting and can be representative of poorly designed ventilation or certain natural ventilation regimes if an occupant only opens 1 or 2 windows [38]. The use of a medium partition resulted in greater particle counts at the receptor when compared to the control, this is due to the specific air flow pattern where there is a large downward jet in the corner of the room (Figure 1). This draws air around the side of the partition, having a particularly strong effect with the medium partition. Traversari showed that small changes in the layout of screens (from 5 full screens and 2 half screens to 6 full screens and 1 half screens) can increase exposure [27]. Together our results demonstrate the complexity that screens can add to indoor air flow, resulting in increases in infection risk that may not be intuitive. In real life scenarios with ventilation that is not well mixed, one could only assess the benefit of partitions with a thorough study of the air flow and there is a very real risk that a partition would increase the exposure of the receptor to airborne infectious material. The largest partition provided a reduction in most particle counts above 1 µm at the receptor, showing protection can be provided by blocking off a large amount of the space. However, this may result in a build-up of particles on the source side of the screen as has been demonstrated in previous CFD studies (e,g,[14]).

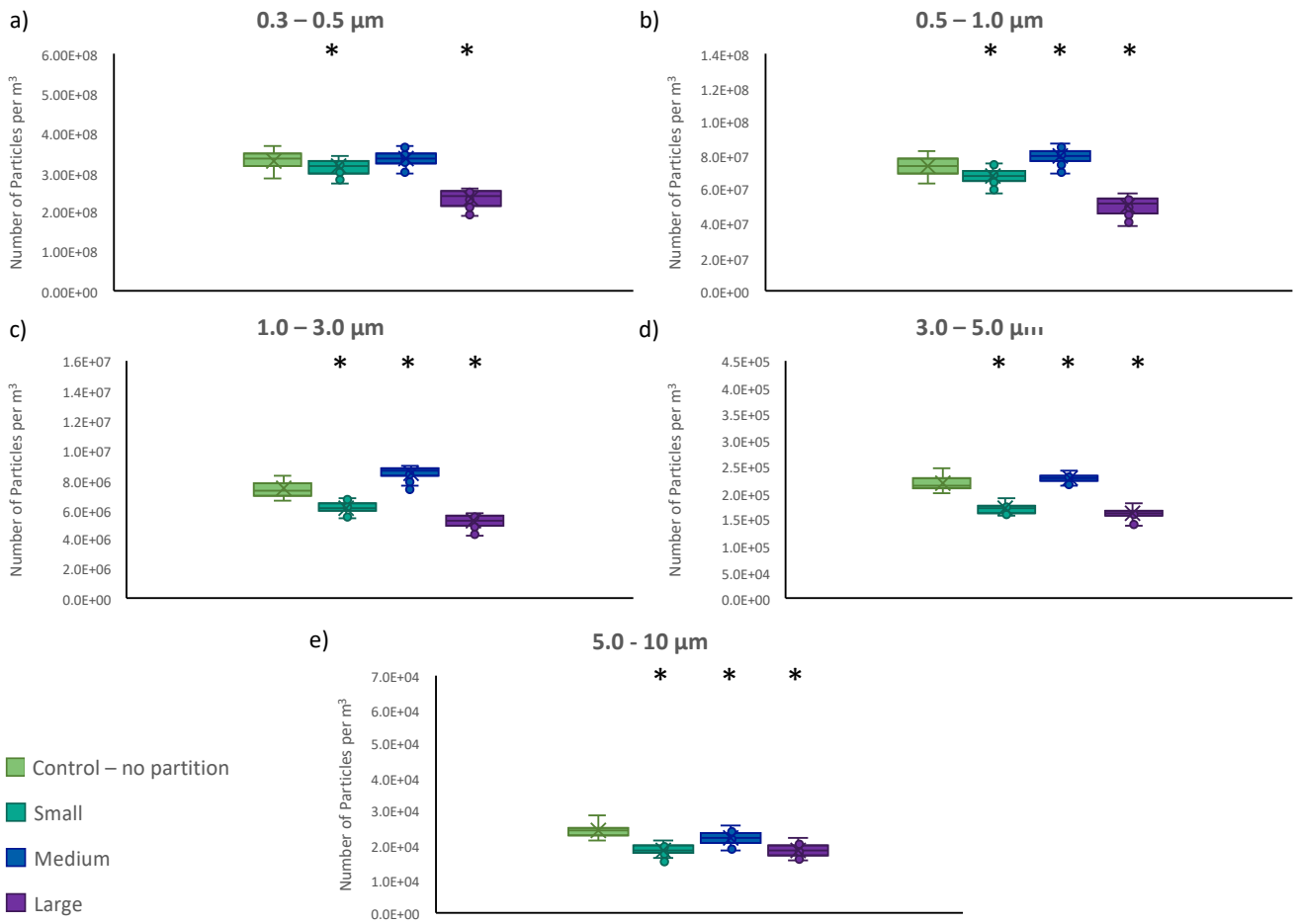


Figure 8: particle counts collected at counter 2 with various partitions in combination with air changes on and mixing fans off. a) 0.3-0.5 µm particles, b) 0.5-1 µm particles, c) 1-3 µm particles, d) 3-5 µm particles, e) 5-10 µm particles. Control, small, medium, and large represent partition strategies. p values of < 0.05 (*) are shown on the graph.

3.2.3 Partitions with well mixed ventilation (Air Changes On and Mixing On)

Figure 9 compares the effect of various partition sizes, when both 5 ac/h and mixing fans are used in the indoor environment. With the additional air movement there is no consistent reduction due to partitions in airborne particles even for the larger particle sizes measured. However, it is worth noting that the particle numbers for those greater than 0.3 µm found at the receptor are approximately an order of magnitude lower than the other scenarios which did not include mixing (3.**2**.1 – 3.**2**.2). Due to this, the impact of partition sizing on absolute numbers of particles at the receptor is much less than in the previous examples. The results show that the use of a large partition had the greatest impact in reducing the number of airborne particles, except for airborne particles >5 µm, whereby average counts slightly increased (7%). Reductions ranged from 3% for airborne particles between 3 µm – 5 µm, to 18% for airborne particles 0.3 – 1.0 µm.

When the ventilation is well mixed the results are variable depending on particle and partition size. Again, the medium partition showed higher airborne counts than expected and the largest partition provided a clear reduction in the majority of particle sizes at the receptor. It

is likely that the high values for the medium partition are due to specific air flows in the space forming due to the jet of air entering interacting with the screen. Although this is not representative of a well-designed environment with multiple air diffusers, it is a situation that may occur due to poor balancing of a ventilation system. Importantly, this work shows that it is possible for the partition to increase the exposure of the receptor and care needs to be taken when the air flows in the space are not understood. Similarly, Zhang *et al*. demonstrated that although partitions significantly reduced exposure with displacement ventilation there was no significant difference when mixing ventilation was used [25]. Combined our results demonstrate that when mixing ventilation is in use there is little benefit of installing partitions. Interestingly Li *et al*. showed a significant reduction due to the presence of a partition in a room ventilated at 4.18 ac/h [28]. No information is provided on the air mixing in the article, but the experimental measurements were undertaken in areas of the room away from diffusers which may have resulted in lower air velocities in these places. As with our results above (3.2.2) this demonstrates the need to understand the air flow dynamics within a space in order to ascertain any potential benefit of installing partitions.

It is worth bearing in mind that, with mixing included, the total number of particles for all partition scenarios and the control study are substantially lower, and therefore the difference in total airborne particle numbers with the different screen sizes is also much lower. Although with mixing in use there is little benefit of the screen the addition of good mixing has a more substantial reduction in airborne particles due to the enhanced dilution and removal.

Interestingly, the number of airborne particles increased slightly with the use of a medium partition, with increases ranging from 0.7% for airborne particles 0.3 – 0.5 μm to 9% for airborne particles 1.0 – 3.0 μm.

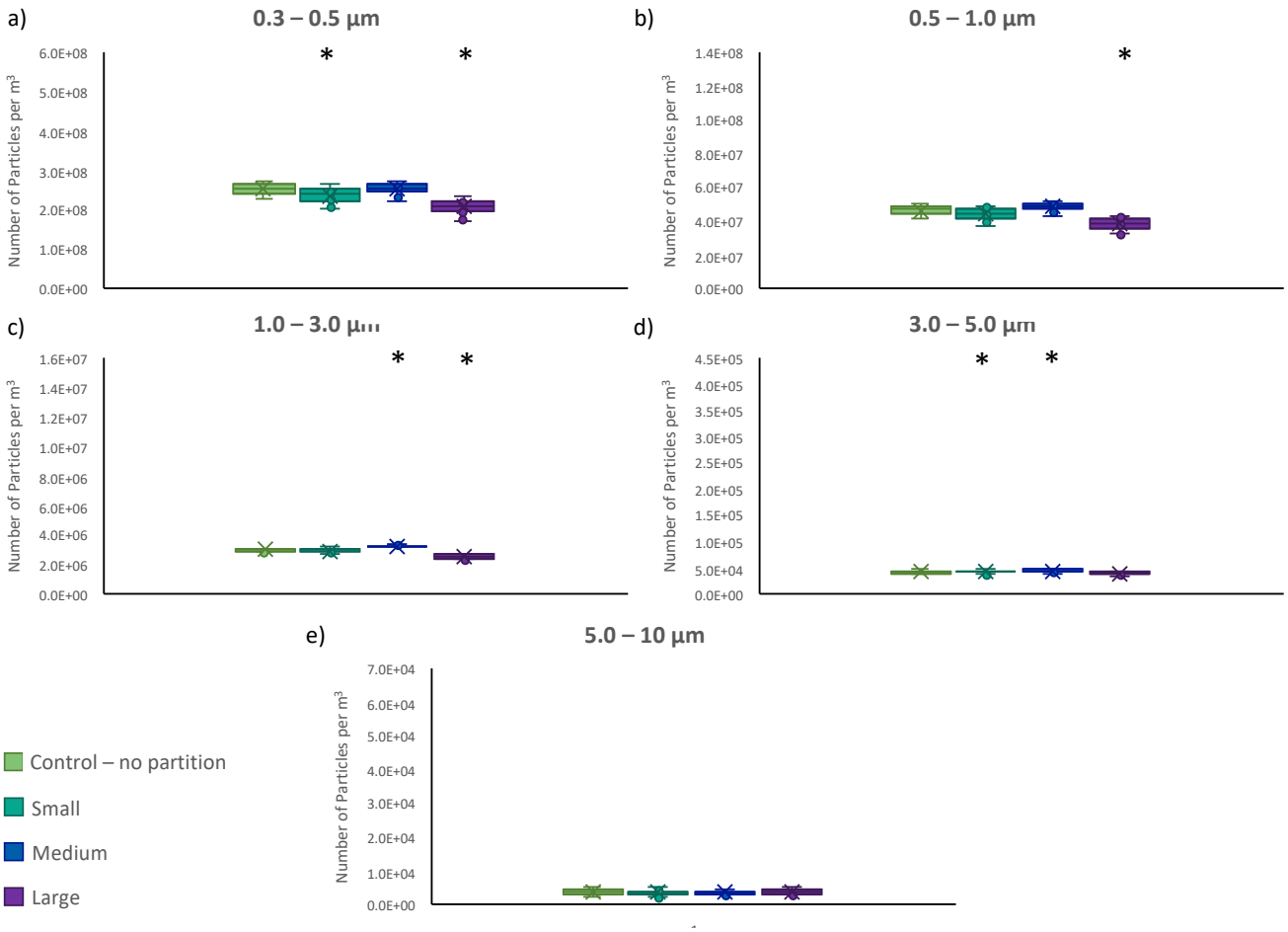


Figure 9: particle counts collected at counter 2 with various partitions in combination with air changes on and mixing fans on. a) 0.3-0.5 µm particles, b) 0.5-1 µm particles, c) 1-3 µm particles, d) 3-5 µm particles, e) 5-10 µm particles. Control, small, medium, and large represent partition strategies. p values of < 0.05 (*) are shown on the graph.

3.3. Summary of impact on airborne counts

Although there is a body of work simulating the use of partitions and impact on the spread of infectious aerosols there are less experimental studies. There have been some case specific studies on schools, offices and hospitals but these do not consider the impact of screen size on resulting airborne and deposited contaminants in the space [21,26,27,29] .The most generalisable and relevant study was conducted by Zhang *et al.* (2022) who compared two different screen sizes with both displacement and mixing ventilation [25]. Whilst a valuable study, it highlighted the need to consider further scenarios, and did not include environments with no ventilation and poor ventilation efficiency which is provided here. Zhang *et al.* showed the impact of physical dividers depends on ventilation type; the addition of barriers in a displacement ventilation scenario showed a substantial reduction, whereas this was not significant with mixing ventilation [25]. These findings concur with our work that has shown reducing impacts of the dividers as the room air flow increases. As with most existing literature, Zhang *et al.* focussed only on airborne particulates and not the changes in location and quantity of infectious material deposited which is discussed below.

3.4. Deposition Studies

Figure 10 compares droplet deposition when four different physical divider strategies were used. In these experiments, all environmental conditions remained the same at 20°C, 50% humidity, 5 ac/h and no mixing fans. These results show that, in general, there is a positive correlation between partition size and the percentage of CaMV DNA deposition on the chamber walls. As the partition size increases, the percentage of DNA deposition on the chamber walls increases. The medium partition gave rise to the highest percentage of DNA deposition on the walls. Whilst little difference was observed between the control and small partition.

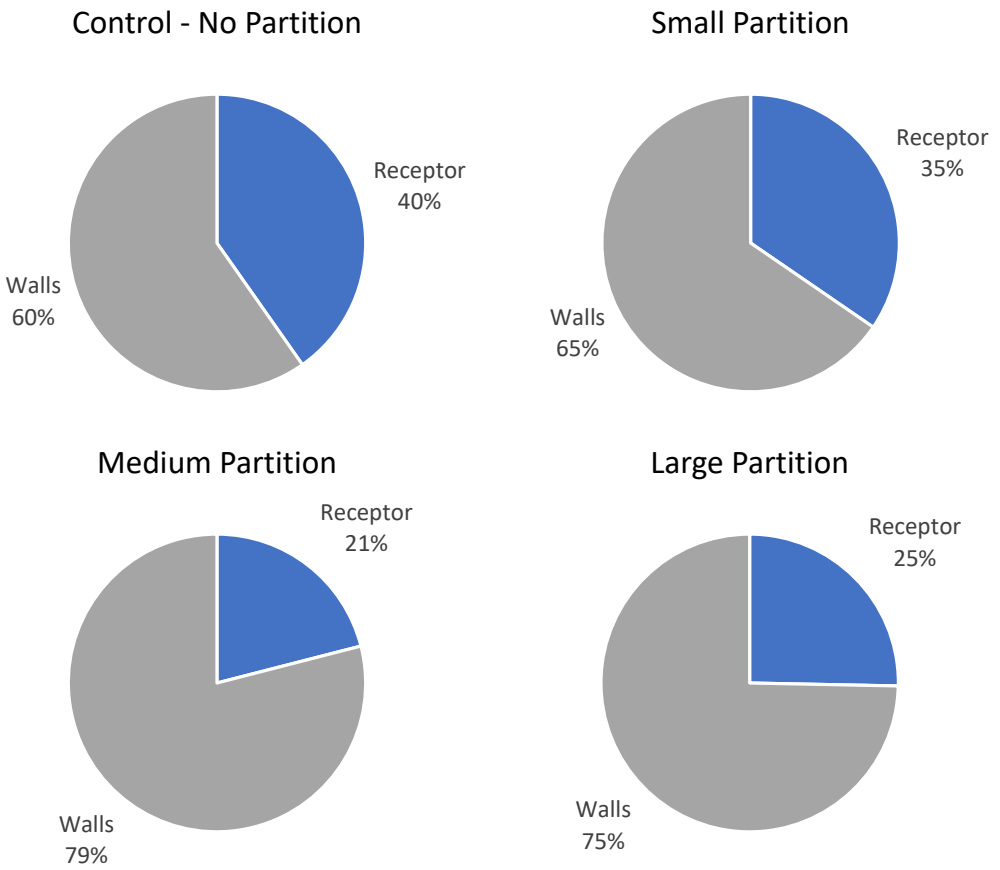


Figure 10: percentage of DNA deposition found at the receptor position and on the chamber walls using various partition strategies. All experiments were carried out at 20°C, 50% humidity, 5 ac/h and mixing fans off.

Figure 11 compares the percentage of droplet deposition at various positions on the partitions when used. From these results, the medium and large partition had greatest percentage of deposition on the source side. There was no deposition in the centre of the partition on the receptor side.

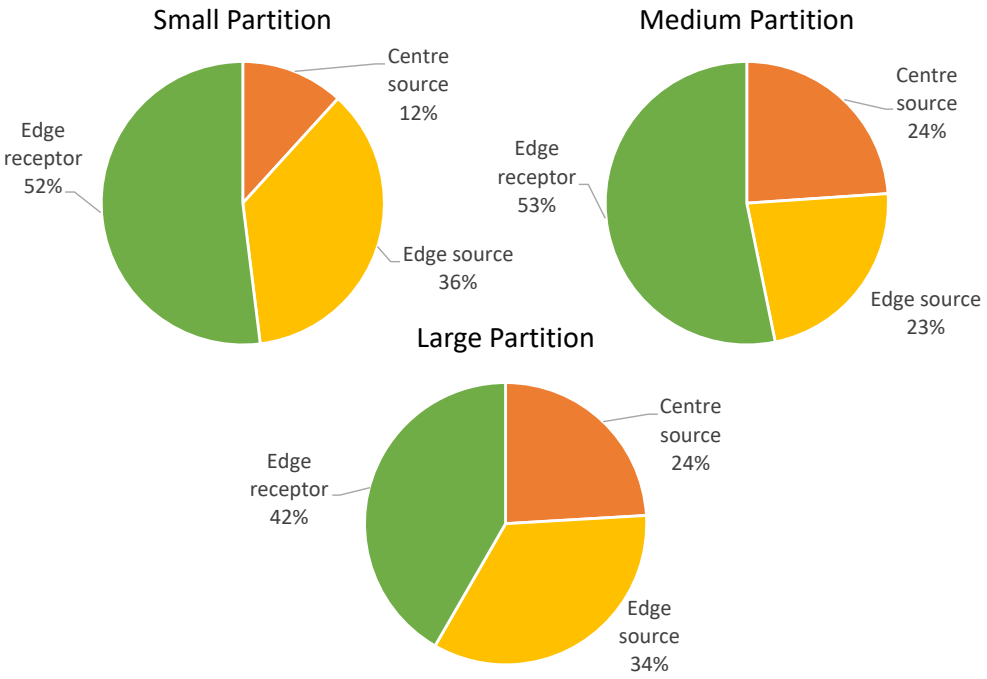


Figure 11: percentage of DNA deposition found on different areas of the partitions. Edge receptor – edges of the partition on the receptor side; edge source – edges of the partition on the source side; centre source – centre of partition on source side exactly opposite the source. All experiments were carried out at 20°C, 50% humidity, 5 ac/h and mixing fans off.

Deposition can provide an important removal mechanism from the air. However, it may also contaminate surfaces resulting in a greater risk of picking up infectious material on a person's hands. Therefore, it is important to understand how the partitions affect the deposition in the space both in terms of understanding the removal mechanisms and understanding the potential need for enhanced cleaning. Both medium and large partitions reduced the deposition at the receptor and increased deposition on the walls. These partitions also increased the proportion of deposition on the source side of the partition (thereby reducing infectious particles in the air). In contrast, the smaller partition had a greater amount of particles moving around to the receptor side and depositing on its edges. Any deposition on the receptor side has the potential to be picked up by the receptor.

3.5. Discussion summary

Overall, increasing ventilation and air movement provides a much greater removal of airborne particles than partitions. Partitions can provide some benefit when there is no ventilation. However, as soon as ventilation is provided, care needs to be taken to avoid unintentionally increasingly the amount of infectious material on the receptor side of a partition. When ventilation is available, larger partitions that provide a substantial barrier in the space reduce particle transfer to the receptor. Larger partitions also resulted in more deposition on the walls and the source side of the partition. When the air is well mixed partitions provide little

additional reduction in airborne counts. If partitions are to be installed, their location in the space, in relation to ventilation inlets and outlets, is of high importance as it can result in unpredictable air movements and deposition patterns.

Partitions may be used to protect from more direct attacks on the receptor's safety, for instance deliberate/accidental spitting in shops/police stations/ medical centres. These scenarios were not tested in this study. In these situations, there may be a benefit of the partition. However, where good ventilation is also provided the decision to use one needs to balance the potential increase in airborne infectious material at the receptor with the benefits to their personal safety.

3.6. Study limitations

The nebuliser used produced aerosols ranging in size from 0.02 to greater than 10 µm, with the majority below 4 µ m. Consequently, we were unable to precisely assess the partition's effectiveness in removing larger particles (e.g >10 µm) that might arise during coughing, shouting, or sneezing. However, the study did reveal a notable reduction in particles in the larger particles measured, including those in the category 5-10 µm, especially in scenarios with no ventilation. This trend is likely to persist when dealing with larger sample sizes. However, it is not possible to say whether the partitions would be more consistent at removing larger particles even with the use of ventilation and mixing.

Although we were only able to measure particles larger than 0.3 µm, even at this size, the partitions had minimal impact at the receptor. This effect is likely to persist when dealing with smaller aerosols. It is worth noting that as we were aerosolising artificial saliva the particle sizes reported are that measured at the receptor, not those generated by the nebuliser as these may have evaporated to a small size before being measured.

The air speeds in the chamber when mixing is in use are higher than would typically be seen in an indoor environment and the lack of diffuser on the inlet results in specific flow patterns. However, it is common for real indoor spaces to perform poorly in terms of ventilation, and this still provides a useful comparison between addition of airflows, increasing mixing and addition of partitions. Future studies investigating a larger space with multiple air diffusers and lower air speeds to assess the benefit of partitions in such an environment would be beneficial.

It should also be noted that particle concentration distribution patterns strongly relate to the source and partition position, which is subsequently affected by the specific airflow field generated by the ceiling fans in the chamber. In this case, only the source and receptor in the central position were tested and results are likely to vary if these are located near walls. However, the over-arching conclusion that there is a risk of the partitions increasing the number of airborne particles near the receptor in certain airflow fields is still valid.

4. Conclusion

During the COVID-19 pandemic plastic partitions were commonly used to protect workers from any potentially infectious aerosols generated by customers or colleagues and in some scenarios (e.g. shops) these are still often in use. In preparation for a future pandemic, it is essential to understand what protection, or risks, are created by the use of these barriers.

This study builds on existing evidence to quantify not just the changes in airborne particles with the provision of partitions but also the change in deposition. Changes in partition sizes and ventilation regime altered both deposited and airborne counts at the receptor side of a protective partition. In situations with no ventilation, it was clear that partitions provided some protection, in particular reducing larger particles over 5-10 μm resulting in a 33 % reduction. When ventilation was provided and mixing increased, then the benefits of partitions reduced and could cause increases in airborne counts at the receptor. Only the largest partitions in these scenarios showed reduced numbers of airborne particles at the receptor reducing 0.3-1 μm aerosols by 18 % and 3-5 μm aerosols by 3 %. However, deposition studies still clearly showed deposition on the screens and therefore some removal from the air. Overall protective barriers can be useful in reducing airborne particles, and therefore risk of infectious disease transmission, in unventilated spaces. However, once ventilation is provided then there is a risk that airborne particles inhaled by a receptor increases. Investing in improved ventilation gives substantially greater reductions in airborne particles, and therefore infection risk, than the addition of partitions. This work provides clear experimental evidence for prioritising investment in improved ventilation rather than trying to segregate people with partitions. However, it also demonstrates that where unventilated spaces are used partitions will provide some benefit to avoid transmission of airborne particles between people.

Acknowledgements

This work was supported by the UKRI funded AIRBODS (Airborne Infection Reduction through Building Operation and Design for SARS-CoV-2) project [EP/W002779/1]. The authors would like to thank Ms Maisie Milton and Ms Helen Rickard for their help with PCR.

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