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Portable HEPA filtration successfully augments natural-ventilation-mediated airborne particle clearance in a legacy design hospital ward

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SUMMARY

As the severe acute respiratory syndrome coronavirus-2 pandemic has proceeded, ventilation has been recognized increasingly as an important tool in infection control. Many hospitals in Ireland and the UK do not have mechanical ventilation and depend on natural ventilation. The effectiveness of natural ventilation varies with atmospheric conditions and building design. In a challenge test of a legacy design ward, this study showed that portable air filtration significantly increased the clearance of pollutant aerosols of respirable size compared with natural ventilation, and reduced spatial variation in particle persistence. A combination of natural ventilation and portable air filtration is significantly more effective for particle clearance than either intervention alone.

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Introduction

The coronavirus disease 2019 (COVID-19) pandemic has galvanized research into airborne disease transmission, leading to widespread acceptance of severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) transmission by airborne particles, particularly in poorly ventilated indoor environments.

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Large quantities of infectious respiratory aerosols can be released when talking, singing or simply breathing [1], and may accumulate in high concentrations inside inadequately ventilated spaces. Case studies have revealed that SARS-CoV-2 can be viable in aerosols which remain airborne for several hours [2]. This has significant implications for hospital design, and immediate relevance for legacy hospitals in Ireland and the UK which lack mechanical ventilation in most clinical areas.

Poorly ventilated spaces harbouring infectious persons, such as hospital wards, can pose a considerable threat to both patients and healthcare workers, with nosocomial COVID-19 outbreaks reported in the literature [3].

Portable high-efficiency particulate air (HEPA) filtration units have been shown to remove SARS-CoV-2 RNA from air samples taken in COVID-19-surge hospital units [4].

This study reports the effects of a portable air filtration unit (AFU) in clearing a common hospital air pollutant (nebulized salbutamol) from a ward bay under renovation.

Fugitive drug aerosols of respirable size are common in hospitals [5], and are useful proxies for persistence and circulation of infectious particles of respiratory origin. This study compared the effectiveness of natural ventilation and HEPA filtration, alone and in combination, for clearing these aerosols from a legacy design ward bay using continuous measurements of airborne particles.

Methods

This study was conducted on 17th December 2021 in a six-bed legacy ward bay undergoing refurbishment. The bay had a room volume of 171 m^3 (height 2.73 m, window wall—entrance door depth 9.5 m, width 6.6 m), an entrance door sealed with a polythene barrier, and three top-hinged windows on one side, facing 169° [south south-east (SSE)]. There was no heating, ventilation and air conditioning system for air handling. The hospital weather station data gave wind speed of 2.6—5.1 m/s from east-SSE, 97—140°. A PARI LC SPRINT jet nebulizer was placed on a counter 40 cm above the ground and 90 cm from the top left window (furthest patient position from the AFU). The nebulizer used a PARI TurboBOY SX compressor (PARI Medical Ltd, West Byfleet, UK) and 2.5 mL of nebulizer solution Ventolin Nebules (GlaxoSmithKline Ltd, Dublin, Ireland). Nebulization was commenced by turning on the air flow at approximately 10 L/min, and continued to reservoir dryness (approximately 15 min). A total of four tests was performed under different ventilation conditions ('windows open, AFU on', 'AFU alone', 'windows alone' and 'windows closed, AFU off). No experimental subject or mannequin was used. Real-time airborne particulate matter ($PM_{2.5}$) was measured at five locations with individual AirVisual Airnode (IQAir, Goldach, Switzerland) monitors, all placed 1 m off the ground (Figure A1, see online supplementary material). The IQAir instrument uses a laser light scattering technique to determine the concentration ($\mu g/m^3$) of airborne particles which diffuse into the monitor. The detectable size range is 0.3—2.5 μm. Readings obtained from these devices correlate well (R^2=0.5—0.9) with numbers of airborne particles in this size range counted by calibrated actively aspirating laser particle detectors, such as the Optical Particle Sizer [6].

Baseline $PM_{2.5}$ was defined as the mean for the five devices prior to nebulization in the unventilated room, each device recorded over an interval of 45 min immediately before the first nebulization. The mean $PM_{2.5}$ for each different ventilation regime was defined as the mean $PM_{2.5}$ for 20 min after the start of a nebulization period.

Air filtration unit

A single HEPA filtration (H13) device (CC2000, Camfil, Ireland) was placed against the right wall of the bay, 1.5 m from the door. Air intake was from both sides of the device parallel to the wall, and filtered air was expelled forwards into the room. The AFU was operated at half capacity corresponding to the manufacturer-claimed air passage rate of 480 m^3/h at 42 dB. Whenever the AFU was required during the experiment, it was switched on approximately 30 s prior to drug nebulization.

Bronchodilator drugs

The active ingredient in each ampoule of Ventolin was 2.5 mg salbutamol (as sulphate).

Data and statistical analysis

Data recorded by the monitors during the (approximately) 4-h measurement period were imported into R Studio 1.1.383, and processed into appropriate files, subsets and matrices. They were then analysed and plotted, with *P*-values determined using a Mann—Whitney *U*-test. Effective air changes per hour (ACH) were calculated based on the exponential decay of the aerosolized drug, as measured by the reduction in $PM_{2.5}$.

Results

$PM_{2.5}$ concentrations were seen to increase following each salbutamol nebulization procedure performed under different ventilation conditions (Figure 1 and Table I).

Mean peak $PM_{2.5}$ over background was lowest after nebulization in the 'windows open, AFU on' condition, at <75% of the next lowest nebulization condition ('AFU alone') (Table I). The highest calculated ACH was observed during the 'windows open, AFU on' condiiton (Table I). The highest variability in $PM_{2.5}$ between monitors was reported post nebulization in the 'windows alone' condition (Figure 1). The mean $PM_{2.5}$ clearance rate was significantly (P<0.01) higher in the 'windows open, AFU on' condition compared with the 'AFU alone' condition, which, in turn, was significantly higher than the 'windows alone' condition (Table I).

During the 'windows alone' condition, $PM_{2.5}$ concentrations did not return to baseline levels, and AFU supplementation was required for 10 min before the next nebulization (Figure 1). Postnebulizer $PM_{2.5}$ concentrations remained higher for longer closer to the source area in the 'windows alone' condition. Operation of the AFU, with or without open windows, reduced intermonitor $PM_{2.5}$ variations significantly. There was a non-significant trend to reduced $PM_{2.5}$ on the side of the room which received a stream of filtered air.

Due to fluctuating readings and limited observation time, a meaningful value for ACH could not be derived from the PM2.5 decay rate for the 'windows closed, AFU off' condition, where the rates ranged from 1.73 to 10.49 ACH.

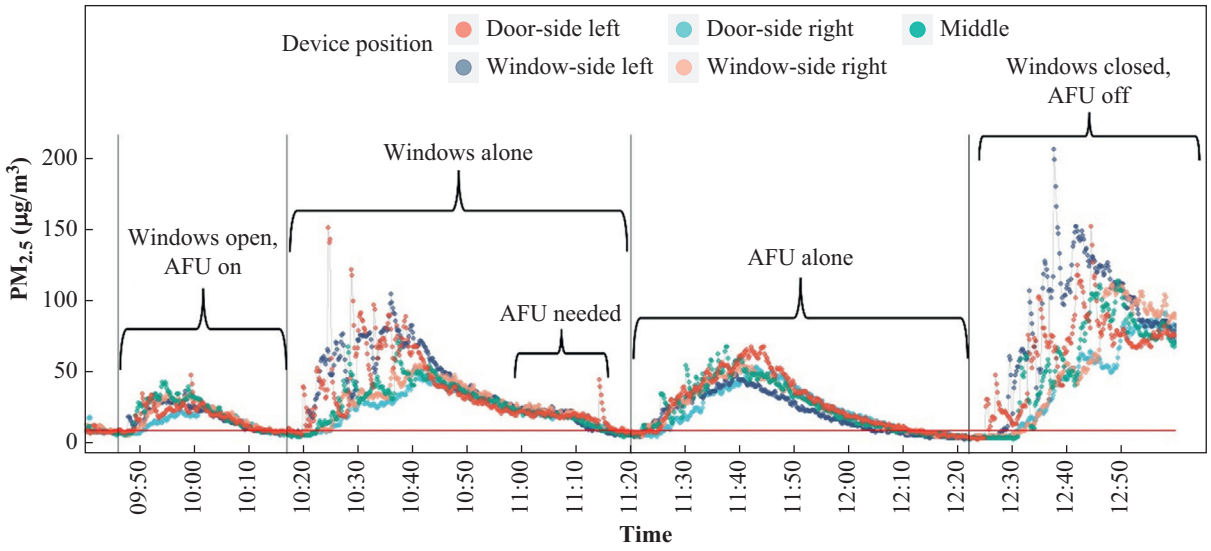

Figure 1. $PM_{2.5}$ (particulate matter with diameter ≤2.5 μm) concentrations (μg/m^3) detected during salbutamol aerosol challenges under four different ventilation conditions in a legacy design hospital bay. $PM_{2.5}$ figures represent summed data per 10 s. The red line denotes background. AFU, air filtration unit.

From the room volume and AFU specification, the theoretical air exchange rate for the AFU in the room was calculated to be 4.44 ACH. The experimental air exchange rate determined from the PM2.5 decay during the 'AFU alone' condition was 4.78 ACH, giving a method error of 0.34 (Table I).

Discussion

All ventilation types were successful in reducing $PM_{2.5}$ concentrations, and the portable AFU successfully augmented natural ventilation in airborne particle clearance from a legacy design hospital ward, both by increasing clearance rate and reducing spatial variability. The 'windows open, AFU on' condition produced the lowest concentrations and highest clearance rate of $PM_{2.5}$. The 'windows alone' condition was unable to reduce concentrations back to baseline levels without aid of the AFU (Figure 1).

Table I
Ventilation types with corresponding $PM_{2.5}$ (particulate matter with diameter ≤2.5 μm) concentrations (μg/m^3) and calculated clearance rates (ACH)

Ventilation type	$PM_{2.5}$ (μg/m^3)[c]	ACH
	Average ± SD	
Background	9.1 ± 1.3	—
Windows open, AFU on	21.9 ± 8.5	11.20 ± 2.93[b]
Windows alone	33.0 ± 25.5	4.52 ± 0.66
AFU alone	28.7 ± 16.2	4.78 ± 0.93[a]
Windows closed, AFU off	61.9 ± 38.0	—

AFU, air filtration unit; SD, standard deviation.
[a] Significantly greater clearance rate than 'windows alone' condition (P<0.01).
[b] Significantly greater clearance rate than 'windows alone' and 'AFU alone' conditions (P<0.01).
[c] Mean $PM_{2.5}$ measured by the five monitors 20 min after the start of nebulization.

It has been reported that the highest titres of airborne SARS-CoV-2 detectable by reverse transcription polymerase chain reaction or culture are in respiratory aerosols of <5 μm diameter [7]. Fugitive bronchodilator drug aerosols are of similar respirable particle size (1.26 μm ± 0.06 μm) [5]. Therefore, clearance of nebulized bronchodilator as reported in this work is a reasonable proxy for clearance of infectious airborne SARS-CoV-2 of respiratory origin.

Addition of an AFU to naturally ventilated healthcare environments improves indoor air quality by increasing the removal of particles of respirable size, effectively supplementing the effect of natural ventilation. The combination of AFU and natural ventilation may be synergistic, possibly because secondary air movement from the AFU increases currents through the windows. Sloof *et al.* proposed a similar phenomenon, suggesting that the reduction in CO_2 during AFU operation may be due to increased entrainment of fresh air from outside through windows due to higher air velocities associated with the AFU [8]. The placement of the AFU in relation to potential particle sources should be considered during deployment. This study shows possible entrainment of particles at the 'door-side left' location (Figure 1), directly downstream of filtered air expelled from the AFU when the windows were closed. This suggests that the AFU should be positioned so that expelled filtered air is not directed at nearby patients. In addition, some AFUs, such as the device used in this study, can be fitted with cowls to deflect expelled air in a desired direction.

For practical reasons, this aerosol challenge study was performed in the absence of patients and healthcare workers. Therefore, the described particle clearances and air changes do not include the effect of human thermal plumes (rising air flows caused by the body:air temperature gradient) or body movements, which would influence ventilation flows in the ward bay in normal use. This is an inevitable limitation of this study.

Unfortunately, due to service pressures requiring rapid re-opening of the ward bay, this study was under considerable time constraints, so another limitation of this study is that each

ventilation type was not repeated, preventing further assessment of the variation in clearance rates. Similarly, due to time constraints, the authors could not record the full decay of the nebulized aerosols during the last phase of the experiment with no ventilation ('windows closed, AFU off' condition).

Current National Health Service England guidelines (also apply to Wales, and very similar to those in Scotland) make natural ventilation the first choice for healthcare settings, but note that variable flow rates are inevitable with this approach, and a minimum achievable natural ventilation rate cannot be specified [9]. They counsel against the use of windows for natural ventilation, instead recommending the use of purpose-built apertures that can be controlled by dampers [9]. The guidelines specify the room dimensions necessary for natural ventilation, and note that single-sided ventilation, such as in the ward bay tested in this study, is only effective to a maximum depth of 3 m. For buildings or room dimensions exceeding specified limits, mixed-mode ventilation (natural ventilation supplemented by mechanical ventilation) or mechanical ventilation alone is required [9]. The guidelines recommend a minimum of 6 ACH for general wards (level 0 and level 1 care) with mixed-mode or mechanical ventilation [9]. In this study, a particle clearance rate corresponding to this ventilation rate was only achieved in the 'windows open, AFU on' condition (Table I). Interestingly, 19th century British guidelines for hospital design maximized natural ventilation, specifying minimum ceiling heights and windows in opposite facades, with limits on interfacade room depth which would meet the current natural ventilation recommendations [10]. These design precepts underlie the 'Nightingale wards' found in most hospitals built in Britain and Ireland from the 1850s to 1939. Many hospital buildings in Ireland and the UK designed and constructed post 1940, such as the ward bay used in this study, lack mechanical ventilation and do not meet design criteria for effective natural ventilation. For this legacy estate, the data show that air filtration can offer useful supplementation which is at least additive with natural ventilation in clearing respirable airborne particles. In addition, low-cost sensors with $PM_{2.5}$ monitoring capability can be a simple and effective method for assessing indoor ventilation and air quality.

Ethical approval

Ethical approval was granted by the Clinical Research Ethics Committee of Cork Teaching Hospitals [Application No. ECM 4 (f) 08 09 2020].

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Conflict of interest statement
None declared.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhin.2022.09.017.

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