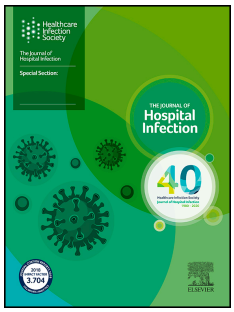
Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Journal Pre-proof



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

Mehael Fennelly, Stig Hellebust, John Wenger, David O'Connor, Gareth W. Griffiths, Barry J. Plant, Michael B. Prentice

PII: S0195-6701(22)00312-7

DOI: https://doi.org/10.1016/j.jhin.2022.09.017

Reference: YJHIN 6761

To appear in: *Journal of Hospital Infection*

Received Date: 22 August 2022

Revised Date: 23 September 2022

Accepted Date: 26 September 2022

Please cite this article as: Fennelly M, Hellebust S, Wenger J, O'Connor D, Griffiths GW, Plant BJ, Prentice MB, Portable HEPA filtration successfully augments natural ventilation-mediated airborne particle clearance in a legacy design hospital ward, *Journal of Hospital Infection*, https://doi.org/10.1016/j.jhin.2022.09.017.

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

Mehael Fennelly[1, 2, 3*], Stig Hellebust[1], John Wenger[1],

David O'Connor[4], Gareth W. Griffiths[5], Barry J Plant[6] and Michael B Prentice[2, 7*]

[1] School of Chemistry and Environmental Research Institute, University College Cork,

[2] Department of Pathology, University College Cork,

[3] School of Chemical and Pharmaceutical Sciences, Technological University Dublin

[4] School of Chemical Sciences Dublin City University,

[5] Department of Life Sciences, Aberystwyth University, Wales,

[6] Adult Cystic Fibrosis Centre, Cork University Hospital, University College Cork,

[7] APC Microbiome Institute, University College Cork

* To whom correspondence should be addressed

mehael.fennelly@tudublin.ie

Room CQ-441, Central Quad, Grangegorman, Dublin 7, D07 H6K8

m.prentice@ucc.ie

UCC Department of Pathology, Cork University Hospital, Wilton, Cork T12 EC8P, Ireland

Running Title:

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

Summary:

As the SARS-CoV-2 pandemic has proceeded, ventilation has been increasingly recognised 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, we show that portable air filtration significantly increases clearance of pollutant aerosols of respirable size compared with natural ventilation and reduces spatial variation in particle persistence. Combined natural ventilation and portable air filtration are significantly more effective in particle clearance than either intervention alone.

Keywords:

Airborne; environment; filtration; HEPA; continuous monitoring; low-cost sensors

Introduction:

The COVID-19 pandemic has galvanised research into airborne disease transmission, leading to widespread acceptance of SARS-CoV-2 transmission by airborne particles, particularly in poorly-ventilated indoor environments.

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 lacking 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 (HCWs), 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].

Here we report the effect of a portable air filtration unit (AFU) in clearing a common hospital air pollutant (nebulised 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. We compare 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:

The study was conducted on December 17th 2021 in a 6-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 (HVAC) system for air handling. The hospital weather station data gave wind speed of 2.6 - 5.1 m/s from East-SSE 97-140 degrees. A PARI LC SPRINT jet nebuliser 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 nebuliser used a PARI TurboBOY SX compressor (PARI Medical Ltd, Surrey, UK) and 2.5 ml of nebuliser solution Ventolin® Nebules® (GlaxoSmithKline Ltd, Dublin, Ireland). Nebulisation was commenced by turning on the airflow at ~10 L/min and continued to reservoir dryness (~15 minutes). A total of four tests was performed under different ventilation conditions (window open filter on, filter only, window only, and window closed filter 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, Switzerland) monitors, all placed 1 m off the ground (Supplementary material, Figure A1). 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 μm to 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 nebulisation in the unventilated room, each device recorded over an interval of 45 minutes immediately before the first nebulisation. The mean $PM_{2.5}$ for each different ventilation regime was defined as the mean $PM_{2.5}$ for 20 minutes after the start of a nebulisation period.

AFU

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 manufacturer claimed air passage rates of 480 m^3/hr at 42 dB. Whenever AFU was required during the experiment it was switched on approximately 30 seconds prior to drug nebulisation.

Bronchodilator drugs

Ventolin® Nebules® (GlaxoSmithKline Ltd, Dublin, Ireland), the active ingredient in each ampoule 2.5 mg salbutamol (as sulphate).

Data and statistical analysis

Data recorded by the monitors during the ~ 4-hour 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. Air changes per hour (ACH) were calculated based on the exponential decay of the aerosolised drug as measured by the reduction of $PM_{2.5}$.

Results:

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

Mean peak $PM_{2.5}$ over background was lowest after nebulisation with open windows and AFU operation, less than 75% of the next lowest nebulisation condition of AFU only (Table I). Highest calculated air changes per hour (ACH) were observed during combined AFU and window ventilation (Table I). Highest variability of $PM_{2.5}$ between different monitors was reported during the post nebulisation period with open windows and AFU off (Figure 1). Mean $PM_{2.5}$ clearance rate was significantly ($P<0.01$) higher with open windows and working AFU than AFU alone, in turn significantly higher than windows alone (Table I).

During the window open without AFU period $PM_{2.5}$ concentrations did not return to baseline levels, and AFU supplementation was required for 10 minutes before the next nebulisation (Figure 1). Post nebuliser $PM_{2.5}$ concentrations remained higher for longer closer to the source area with "Window Only" ventilation. Operation of the AFU, with or without open windows, reduced inter-monitor $PM_{2.5}$ 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 $PM_{2.5}$ decay rate derived CADR figure could not be calculated for the final period with the window closed and the AFU off, where the rates ranged from 1.73 – 10.49 ACH.

From the room volume and AFU air exchange rate the theoretical clean air delivery rate (CADR) of the AFU for the room was determined to be 4.44 ACH. The calculated experimental CADR during the AFU only period 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 a 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 combination of Window and AFU produced the lowest concentrations and highest clearance rate of $PM_{2.5}$. "Window Only" was unable to reduce concentrations back down to baseline levels without aid of the AFU (Figure 1).

It has been reported that the highest titres of airborne SARS-CoV-2 detectable by RT-PCR or culture are in respiratory aerosols <5 μm diameter [7]. Fugitive bronchodilator drug aerosols are of similar respirable particle size (1.26 μm ± 0.06 μm) [5]. Therefore, clearance of nebulised 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 removal of particles of respirable size, effectively supplementing the effect of natural ventilation. Combined AFU and natural ventilation may be more than additive, possibly because secondary air movement from the filter increases currents through the windows. Sloof *et al.* proposed a similar phenomenon suggesting that 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 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 location door side left (Fig 1) directly downstream of filtered air expelled from the AFU when the windows were closed. This suggests the AFU should be positioned so expelled filtered air is not directed at nearby patients. In addition, some AFU, 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 airflows caused by the body to air temperature gradient),

or body movements, which would influence ventilation flows in the ward bay in normal use. This is an inevitable limitation on our conclusions.

Unfortunately, due to service pressures requiring speedy re-opening of the ward bay this study was under considerable time constraints, so one limitation is that each ventilation type was not repeated, preventing further assessment of clearance rate variation. Similarly, due to time constraints the authors could not record the full decay of the nebulised aerosols during the last phase of the experiment with no ventilation.

Current National Health Service (NHS) 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 controllable by dampers [9]. The guidelines specify room dimensions necessary for natural ventilation and note that single sided ventilation, such as in the ward bay we tested, 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 air changes per hour 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 with the combination of the AFU and natural ventilation (Table I). Interestingly, 19th century British guidelines for hospital design maximised natural ventilation, specifying minimum ceiling heights, and windows in opposite facades, with limits on inter-facade 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 our own ward bay, lack mechanical ventilation and do not meet design criteria for effective natural ventilation. For this legacy estate, our 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.

References

1. Gregson FK, Watson NA, Orton CM, Haddrell AE, McCarthy LP, Finnie TJ *et al.* Comparing aerosol concentrations and particle size distributions generated by singing, speaking and breathing. *Aerosol Science and Technology* 2021; **55**: 681-91.
2. Van Doremalen N, Bushmaker T, Morris DH, Holbrook MG, Gamble A, Williamson BN *et al.* Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. *New England Journal of Medicine* 2020; **382**: 1564-7.
3. Piapan L, De Michieli P, Ronchese F, Rui F, Peresson M, Segat L *et al.* COVID-19 outbreaks in hospital workers during the first COVID-19 wave. *Occupational Medicine* 2022; **72**: 110-7.
4. Conway Morris A, Sharrocks K, Bousfield R, Kermack L, Maes M, Higginson E *et al.* The removal of airborne SARS-CoV-2 and other microbial bioaerosols by air filtration on COVID-19 surge units. *Clinical infectious diseases : an official publication of the Infectious Diseases Society of America* 2021; doi 10.1093/cid/ciab933: ciab933.
5. Fennelly M, Keane J, Dolan L, Plant B, O'Connor D, Sodeau J *et al.* Containment of procedure-associated aerosols by an extractor tent: effect on nebulized drug particle dispersal. *Journal of Hospital Infection* 2021; **110**: 108-13.
6. Sankhyan S, Witteman JK, Coyan S, Patel S, Vance ME Assessment of PM2.5 concentrations, transport, and mitigation in indoor environments using low-cost air quality monitors and a portable air cleaner. *Environmental Science: Atmospheres* 2022; **2**: 647-58.
7. Santarpia JL, Herrera VL, Rivera DN, Ratnesar-Shumate S, Reid SP, Ackerman DN *et al.* The size and culturability of patient-generated SARS-CoV-2 aerosol. *Journal of Exposure Science & Environmental Epidemiology* 2021; doi 10.1038/s41370-021-00376-8.
8. Sloof D, Butler MB, Peters C, Morris AC, Gouliouris T, Thaxter R *et al.* Impact of supplementary air filtration on airborne particulate matter in a UK hospital ward. *medRxiv* 2022; doi https://doi.org/10.1101/2022.03.25.22272953.
9. NHS England and NHS Improvement Health technical memorandum HTM 03-01: Specialised ventilation for healthcare premises, Part A: Design and validation. 2021.
10. Nightingale F Notes on Hospitals, Longman, Green, Longman. 1863.

Tables

Table I Ventilation types with corresponding $PM_{2.5}$ concentrations ($\mu g/m^3$) and calculated clearance rates (CADR).

Ventilation Type	$PM_{2.5}$ ($\mu g/m^3$)	Clearance Rates (CADR)
	Average ± SD	
Background	9.1 ± 1.3	-
Window and AFU	21.9 ± 8.5	11.20 ± 2.93 **
Window Only	33.0 ± 25.5	4.52 ± 0.66
AFU Only	28.7 ± 16.2	4.78 ± 0.93 *
None	61.9 ± 38.0	-

* Significantly greater clearance rate than window only ($P < 0.01$)

** Significantly greater clearance rate than window only and AFU only ($P < 0.01$)

Mean $PM_{2.5}$ during a period of 20-minutes after the start of nebulisation measured by 5 monitors

Figure

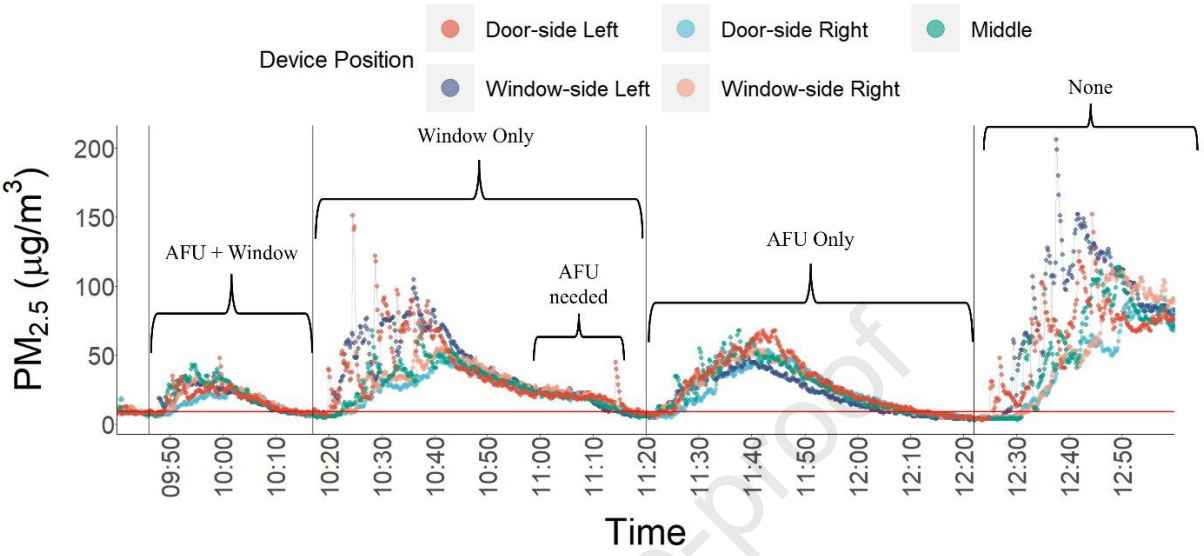


Figure 1. $PM_{2.5}$ concentrations ($\mu g/m^3$) detected during salbutamol aerosol challenges under four different ventilation conditions in a legacy design hospital bay. $PM_{2.5}$ figures represent summed data per 10 seconds. Red-line denotes background.

Acknowledgements

The authors thank Mr PJ Murphy, Cork University Hospital (CUH) Estates, and Dr G O'Callaghan Chief Executive Officer CUH for facilitating this study. Ethical approval was granted by the Clinical Research Ethics Committee of the Cork Teaching Hospitals, Application Number ECM 4 (f) 08 09 2020. This manuscript emanated from research conducted with the financial support of Science Foundation Ireland (Grant No. 20-COV-0281).