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SCIENTIFIC LETTER

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Point of emission air filtration enhances protection of healthcare workers against skin contamination with virus aerosol

To the Editors:

The World Health Organization (WHO) and Centres for Disease Control and Prevention (CDC) recently updated their advice regarding airborne transmission of SARS-CoV-2,[1,2] highlighting that virus-laden aerosols can travel large distances and remain suspended in air for prolonged periods of time. Coupled with recent data suggesting that the Delta variant of concern is more transmissible[3] and results in higher likelihood of admission to hospital,[4] the need to address virus aerosol transmission has never been greater.

Several studies have highlighted the effectiveness of aerosol control measures using point of emission air exchange/filtration.[5,6] This strategy employs a containment structure (e.g., hood) and an expensive/hospital-grade air purifier with a high-efficiency particulate air (HEPA) filter. We recently demonstrated that this method eliminates environmental contamination when very large quantities of bacteriophage virus are experimentally aerosolized into a non-ventilated clinical room.[6] While this method is relatively low cost compared to building/infrastructure alteration, it is unclear whether similar efficacy can be achieved with an 'off the shelf' air purifiers. Furthermore, it is not known if currently deployed personal protective equipment (PPE) strategies protect against virus aerosol transmission to healthcare workers, or if point of emission control of virus aerosol can enhance the effectiveness of PPE.

In this context, we used a bacteriophage 'live' virus model of aerosol transmission to:

1. Assess the ability of an 'off the shelf' air purifier and hood to reduce environmental contamination,
2. Assess the effectiveness of a commonly deployed PPE strategy to protect against skin contamination and
3. Determine if the protection offered by PPE can be enhanced by a point of emission aerosol control strategy.

Utilizing our previously described method,[6] we systematically tested virus aerosol surface contamination of a clinical room and skin contamination of a healthcare worker wearing a gown (Jiangxi Fashionwind Apparel Co. Ltd.), disposable gloves (Mediflex Industries), face shield (Xamen Sanmiss Bags Co.) and an N95 respirator (BYD Precision Manufacture Co., Ltd.). We nebulized (Pari-Pep S System, PARI) a total of 10^9 (10 ml of 10^8) PhiX174 bacteriophages into a sealed clinical room with dimensions: 4.0 × 3.25 × 2.7 m (surface area = 13.0 m^2, volume = 35.1 m^3). Surface contamination was detected by 13 soft agar overlays containing *Escherichia coli C* bacterial host left uncovered for the duration that bacteriophage lysate was nebulized (~40 min). Plates were sealed after nebulization and new plates were exposed over two consecutive 15 min intervals to quantify residual virus settling. After a total exposure period of 70 min, the healthcare worker exited the room. Personal contamination was determined by skin swab following doffing of PPE. The doffing procedure was video recorded and examined independently by two expert nurses to ensure doffing procedure compliance. Doffing occurred in a clinical room separated from the testing room by a corridor and four sealed doors. The doffing room had continuous HEPA filtration (five exchanges per hour) at all times. Control plates were opened at the time of doffing/swabbing to determine if any viruses were present during the doffing/swabbing procedure. Swabs (Jumbo Swabs, Multigate Medical Products Pty Ltd.) were individually immersed in 3 ml of 1× PBS contained in a test tube, and then applied individually to four separate areas—(1) forearms and back of hands, (2) neck, (3) forehead and (4) under the N95 mask (around mouth/nose under mask coverage). Swabs were re-immersed in the PBS within the test tube, vigorously mixed with 1 ml of PBS collected and plated neatly with bacterial host to obtain virus count from each individual swab.

Surface and personal contamination was assessed across three experimental conditions:

1. No air filtration or hood structure applied (control condition).
2. Air filtration and hood applied with 'off the shelf' HEPA filter applied at 270 m^3/h (1000i series, Philips, Amsterdam, The Netherlands).
3. Air filtration and hood applied with hospital-grade HEPA filter set to 240 m^3/h (IQAir HealthPro250, Swiss Made, Goldach, Switzerland).

Each experimental condition was repeated three times. Kruskal–Wallis with uncorrected Dunn's post hoc test was used to compare virus counts between conditions for settle plates and for each skin swab area. The room was purged

for 30 min using the hospital-grade HEPA filter set to 470 m^3/h. Control plates were left uncovered post-purge to confirm decontamination was complete.

The control condition demonstrated extensive environmental and also limited skin contamination underneath PPE, which was highest on the nose/mouth (Figure 1). The 'off the shelf' air purifier filter and hood provided environmental control of virus aerosol and almost zero skin contamination. In comparison, the hospital-grade air purifier provided complete environmental and skin contamination protection, despite a lower clean air delivery rate (CADR, 240 vs. 270 m^3/h). Virus counts on plates were significantly lower for both air purifiers across all three time intervals. Similarly, virus counts from skin swabs were significantly lower on neck, forehead and under the N95 (all $p < 0.05$). There were no statistically significant differences in detected virus counts between the IQAir and Philips 1000i air purifiers.

To our knowledge, this is the first study to explore the interaction between air purification and PPE in protecting against virus aerosol. We demonstrate that widely used PPE provides incomplete protection against skin contamination from prolonged (70 min) exposure to an environment with a high number of virus-laden aerosols and poor ventilation.

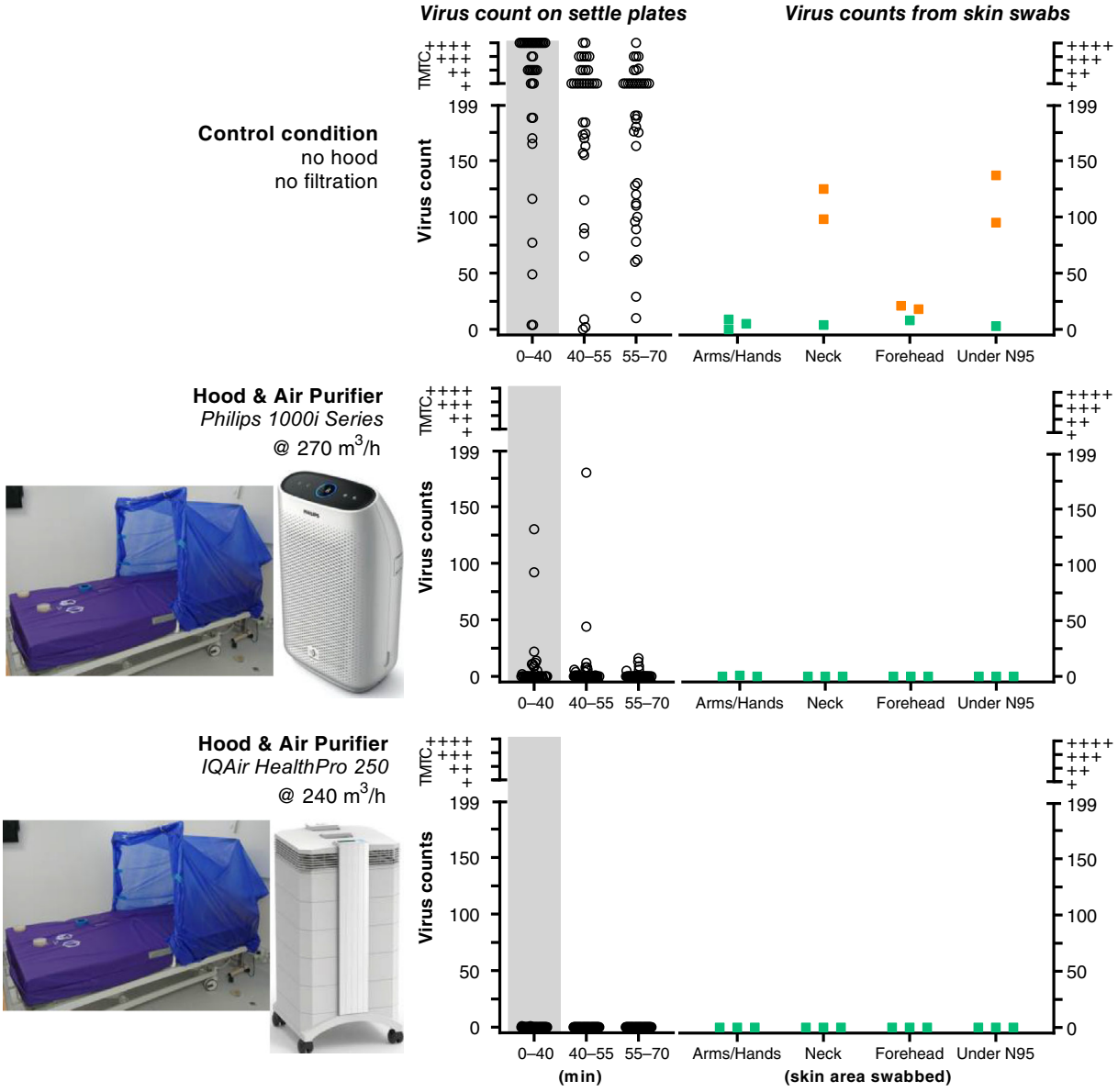

FIGURE 1 Virus plaque counts per experimental condition. Graphs on the left quantify environmental contamination in the clinical room from virus aerosol. Open circles represent virus counts on settling plates and closed circles show plates within 1 m of the aerosol source. Grey bars represent the period of active nebulization (40 min). Plates were closed and new ones reopened over two 15 min intervals after nebulization to quantify residual virus settling over time. Virus counts were quantified as plaque-forming units as previously described.[13] Virus counts >200 were considered too-many-to-count (TMTC) and were rated using an ordinal (+, ++, +++, ++++) visual rating scale. Squares on the right show virus counts determined from skin surface swabs for each condition. Squares are also coded green and amber to reflect qualitative ratings of mild (≤10) and intermediate (11–199) virus counts

Moreover, skin contamination was greatest on the face, beneath a non-fit-tested N95 respirator. This elevated level of contamination compared to other skin sites is likely due to the suction produced by the healthcare worker's respiration (which does not affect other sites). These data demonstrate that the effectiveness of PPE in preventing skin contamination is enhanced by the use of a hood and HEPA filter point of emission control strategy. Even an 'off the shelf' HEPA filter demonstrated a large impact on virus aerosol contamination.

Several studies have demonstrated the efficacy of HEPA filters to remove smoke/chemical aerosols[7–9] in both classrooms and hospital environments. Furthermore, a recent work has shown the ability of a point of emission hood strategy to effectively reduce aerosol particle concentrations generated by humans or other medical equipment such as nebulizers.[5] An important innovation of the current methodology was the use of a marker virus (bacteriophage PhiX174) which further allows the quantification of viable viruses settling on surfaces in the environment as well as the degree of infiltration into PPE.

The COVID-19 pandemic has led to a complete reappraisal of the science and assumptions underpinning infection control practice and virus aerosol transmission. The CDC and WHO now recognize the key importance of virus aerosol transmission to the spread of SARS-CoV-2.[1,2] Thousands of healthcare workers who have been infected with SARS-CoV-2 while treating patients in their workplace and critically, emerging evidence suggests that patients who acquire SARS-CoV-2 infections in hospital have a mortality rate of approximately 30%.[10,11] Our data provide evidence that a simple, cost-effective and scalable approach utilizing a containment at point of emission strategy can negate environmental contamination by virus aerosol and can enhance the effectiveness of PPE in protecting against skin contamination. Commercial products utilizing this mode of air purification (https://medihood.com.au/) have begun to see deployment in Australian hospitals, particularly in open ward settings where it is difficult to exchange large volumes of air, and where hospitalized patients share common air (i.e., no individual rooms).

Our data showing similar performance between the 'off the shelf unit' and a hospital-grade air purifier are important given there are very large differences in price and availability between these devices (Philips 1000i Series recommended retail price [RRP] ∼ $349 AUD, $299 USD vs. IQAir HealthPro250, RRP ∼ $2300 AUD, $849 USD—note that such prices are subject to change and vary between regions). It is important to note that the hospital-grade device is capable of higher CADRs (up to 470 m^3/h) and therefore has a clear advantage when filtering air in larger volume spaces. However, the hood strategy employed in the current study is able to enhance any given CADR by enclosing a small-volume space around the point of emission. When such a strategy is used, a much lower CADR is needed to achieve a high local air exchange/filtration rate compared to more standard deployment in an indoor space.

Our study has some important limitations. First, we deployed a single approach to PPE that utilized a non-fit-tested N95 respirator. Future work is needed to systematically assess the effectiveness of various mask strategies (e.g. fit-tested N95 respirators) in preventing skin contamination of the face. Second, we believe that skin contamination detected underneath the N95 respirator most likely represents the 'tip of the iceberg' of likely virus aerosol contamination of the airway. Given that the nebulizer we use produces 3.4 μm particles,[12] it is likely many of these are being inhaled into the upper and lower respiratory tract beneath the N95 respirator. Finally, we did not explore the interaction between point of emission air filtration and other existing environment control methods such as inbuilt heating ventilation and air conditioning (HVAC) systems. We expect that layered protection provided by multiple environmental control strategies would strongly reduce aerosol transmission in hospital settings. Further work will be required to explore the interaction between multiple control strategies. Each of these issues are ongoing areas of research by our group.

KEYWORDS

aerosol, air filtration, COVID-19, critical care medicine, infection control, personal protective equipment, ventilation

CONFLICT OF INTEREST

None declared.

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HUMAN ETHICS APPROVAL DECLARATION

This study was given an exemption by the Monash Health Human Research Ethics Committee as there were no human or animal research participants.

AUTHOR CONTRIBUTION

Shane A. Landry: Conceptualization (equal); data curation (equal); formal analysis (equal); investigation (equal); methodology (equal); project administration (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Diesh Subedi:** Investigation (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal). **Martin I. MacDonald:** Conceptualization (equal); writing – original draft (equal); writing – review and editing (equal). **Samantha Dix:** Investigation (equal); methodology (equal); validation (equal); writing – original draft (equal); writing – review and editing (equal). **Donna Kutey:** Investigation (equal); methodology (equal); validation (equal); writing – original draft (equal); writing – review and editing (equal). **Jeremy J. Barr:** Conceptualization (equal); investigation (equal); methodology (equal); writing – original draft (equal); writing – review and

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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