
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.

To compare aerosol clearance with and without negative pressure, the humidifier was turned off to simulate the end of an aerosol-generating procedure. Without negative pressure, 183 min was required for the particle count to decrease by 98%, compared with 5 min when negative pressure was applied (Supplementary Fig. 2). Whilst visual inspection correlated with the removal of large aerosolised particles (>10 μm), it was highly unreliable at determining the degree of removal of small aerosolised particles, as the hood appeared clear when particle count of particles greater than 0.5 μm was well above 200 000 $L^{-1}$.

Limitations of the negative-pressure patient isolation hood device include (i) the time required for set-up, albeit a few minutes, might preclude its use in emergency situations; (ii) whilst aerosolised particles are efficiently removed by negative pressure, particles that adhere to the inner surface of the hood remain a source for contamination, so training is required to disassemble and discard the plastic drape; (iii) particles <0.3 μm in size were not measured, although smaller particles may be more susceptible to removal by negative pressure[5]; and (iv) the air in the hood reaches the smoke evacuator and passes through an ultra-low-particulate-air-grade filter that is rated to remove 99.999% of particles >100 μm in size. Filtered air is then recirculated back to the operating theatre. The filter has a limited plume evacuation time; thus, the need for replacement adds to the cost of using the device.

Despite these limitations, the negative-pressure patient isolation hood is expected to reduce the exposure of healthcare workers to aerosols during aerosol-generating procedures, such as tracheal intubation, extubation, and bronchoscopy, and thus may decrease the risk of viral transmission. It may also reduce the risk of cross contamination between patients in operating theatres. The utility of the hood can be broadened to most situations, in which direct patient contact is required, such as transportation, other bedside aerosol-generating procedures (e.g. tracheostomy, tracheal tube suctioning, and open circuit), and during phlebotomy. The negative-pressure patient isolation hood might also enable liberalised use of noninvasive ventilation strategies during the present pandemic in the setting of ventilator shortages. We recommend the use of particle counters to study the effectiveness of similar protective devices, as most devices have not been properly tested and may therefore provide a false sense of security and put their users at increased risk of exposure to droplets and aerosols.

## Declarations of interest

The authors declare that they have no conflicts of interest.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bja.2020.05.002.

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# Rapid clearing of aerosol in an intubation box by vacuum filtration

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Editor—Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is a highly infectious respiratory pathogen disseminated by droplets and aerosols.[1] Healthcare providers (HCPs) performing aerosol-generating procedures (AGPs) on coronavirus disease 2019 (COVID-19) patients are at risk of infection. AGPs include, but are not limited to tracheal intubation, extubation, mask ventilation, tracheostomy, oropharyngeal/tracheal aspiration, high-flow air/oxygen delivery, bronchoscopy, esophagogastroduodenoscopy, transoesophageal echocardiography, defibrillation, chest compression, and a range of dental, head and neck, and thoracic surgeries. Variations of Lai's aerosol barrier[2] for limiting healthcare provider exposures has been rapidly adopted, but remains incompletely validated.[3,4] Cubillos and colleagues[5] reported qualitative results of vacuum filtration, but clinically actionable time-to-clearance information is lacking. Efficacy of particle elimination by vacuum relates to air flow rates, which can be diminished by in-line viral filters essential to decontamination of outflow. Therefore, empirical testing is needed for each vacuum/filter configuration attached to intubation boxes to determine the particle elimination kinetics. Here, we present experimental data on the time course of active aerosol removal, comparing our hospital in-wall suction system and two low-cost commercially-available vacuums using an intubation box.

Our two-piece design intubation box[6] (Fig. 1a) includes active aerosol removal by attaching a vacuum with an in-line high-efficiency viral filter (Draeger SafeStar55$^{R}$, German company). Aerosol removal by such filters could mitigate virus dispersion; this filter has 99.9999% viral filtration efficiency.[7] We tested two vacuums, with stated air flow ratings of 60 cubic feet min$^{-1}$ (CFM; Shop-Vac #9303511) or 23 CFM (Intex (Long Beach, CA, USA) mattress inflator/deflator #66639E), attached via standard airway circuit tubing. Separately, we also attached our hospital wall vacuum through a pressure regulator (Ohio Medical PISA, Gurnee, IL, USA) set to maximum

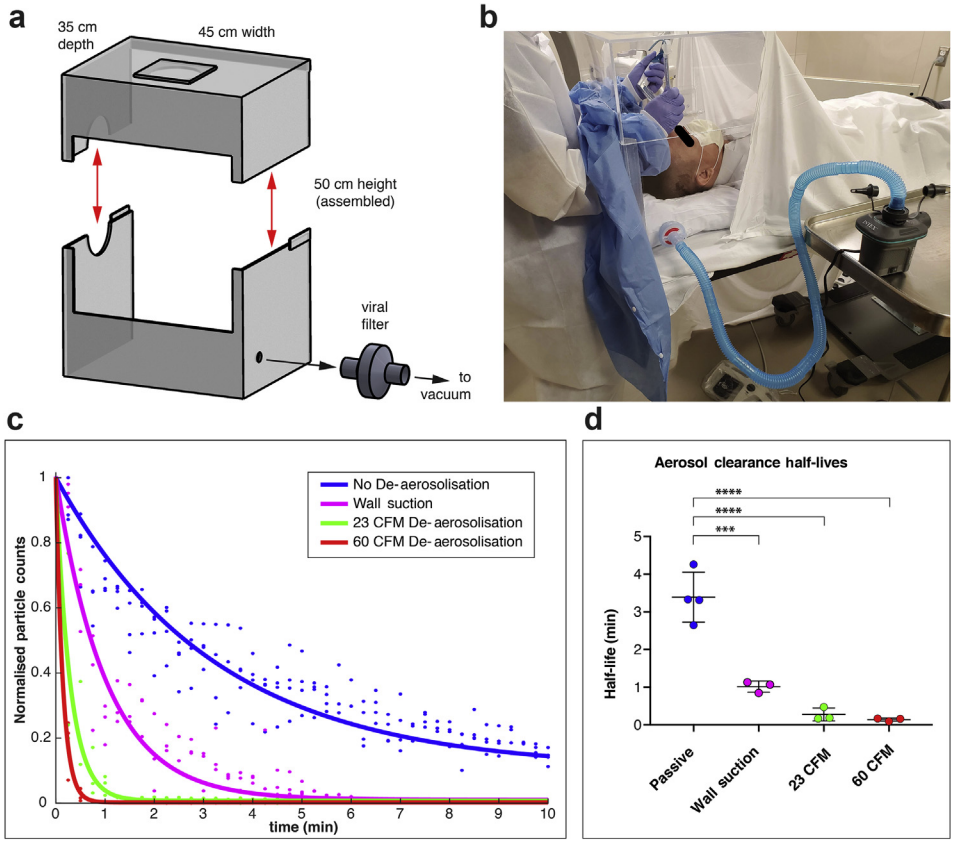


Fig 1. Intubation box with improved mobility and vacuum filtration. (a) The two-piece intubation box with a vacuum and in-line particulate filter is shown as a schematic with overall dimensions shown, with red arrows showing detachable top. (b) A mock intubation setup is shown with the working window sealed with a gown (disposable) clipped into place, affording proceduralist arm mobility, aerosol enclosure, and vacuum elimination. The gown can be easily detached during airway rescue. (c) Aerosol elimination follows exponential decay kinetics, with hospital wall vacuum and two commercial vacuums improving clearance kinetics. (d) Vacuum aerosol removal significantly decreases particle clearance half-lives from 3.4 min (passive) to 1.0 min (wall suction), and to 0.28 min with the 23 cubic feet min$^{-1}$ (CFM) vacuum, or 0.14 min with a 60 CFM vacuum. Time series from replicate experiments from 1c were fit to exponential decays after normalisation, and average half-lives ($t_{1/2}$) were analysed by one-way analysis of variance (ANOVA) ($F(3,9)=52$, overall $P<0.0001$). Aerosol clearance was significantly hastened with suction from the wall vacuum, and with the 23 or 60 CFM stand-alone vacuums *vs* passive clearance. ***$P=0.0001$, ****$P<0.0001$, ANOVA with Tukey's multiple comparisons testing, error bars represent standard deviation.

(0.13 kPa) to a 2 L suction canister, then to the filter and box. In our practice, the patient is covered with a sheet or surgical drape (Fig. 1b).

To simulate viral aerosol contamination and clearance, an aerosol particle generator (TSI 8026, Shoreview, MN, USA) was placed inside the covered 35×45×50 cm plexiglass box. An aerosol particle counter (TSI PortaCount 8048) was connected to a 135 cm long sampling tubing inside the box. To measure baseline particle clearance without vacuum applied, we created a stabilised elevated particle count ($2.5–6\times10^4$ particles $cm^{-3}$); the particle generator was then turned off and particle count data sampled at 15 s intervals in technical replicates. For active aerosol removal, the vacuum source was turned on at the moment when the particle generator was turned off. Normalised counts were fit as exponential decays ($r^2$>0.95, Matlab, Natick, MA, USA) and half-lives analysed by one-way analysis of variance (ANOVA) (Prism 7, GraphPad Software, San Diego, CA, USA) with significance set to $P$<0.05 and Tukey's *post hoc* pairwise comparisons test.

The 3.4 min half-life baseline aerosol clearance was reduced to 1.0 min with the wall vacuum, 0.28 min with the 23 CFM vacuum, and 0.14 min with the 60 CFM vacuum (Fig. 1c, one-way ANOVA, $F(3,9)=52$, overall $P$<0.0001). The two standalone vacuum configurations were not statistically distinguishable ($P$=0.97), though clearance half-lives for each vacuum were shorter than with no vacuum (Fig. 1d, ANOVA *post hoc* Tukey's test: $P$=0.001 for passive *vs* wall suction, $P$<0.0001 for passive *vs* 60 CFM, $P$<0.0001 for passive *vs* 23 CFM).

We applied a vacuum and viral filter to an enclosed intubation box and determined aerosol clearance times in order to establish parameters for time-to-removal after use. Enclosed boxes with vacuums capable of filtering SARS-CoV-2 dispersed during AGPs are likely safer compared with intubation boxes open to the room. The National Institute of Occupational Safety and Health (NIOSH) 'hierarchy of controls' prioritises engineering and administrative controls over personal protective equipment (PPE) for mitigating occupational hazards, and PPE is considered the least effective (albeit indispensable) control.[8] Although we promote this engineering control, proper PPE is still recommended despite any additional benefits offered by our system.

The Occupational Safety and Health Administration (OSHA) recommends US operating rooms maintain a minimum of 15 air changes per hour, equivalent to 99% aerosol removal in 18 min.[9] Both 23 and 60 CFM vacuum pumps reached 99% clearance of the box in 90 s, and likely reduce collateral contamination of other operating room equipment. The reusable 23 CFM vacuum costs $20, and could save several hundred dollars in operating room time per use.[10] Our hospital wall suction significantly reduced clearance times also, but flow rates for wall suction are not routinely controllable nor determinable in clinical practice, precluding broad extrapolation. Aerosol levels outside the box were not assessed, but gases suctioned through a viral filter with 99.9999% efficiency exceed recommended air quality regulations. For longer procedures necessitating aerosol removal, ear plugs should be used and pressures considered.[11] Improvements towards lightweight barriers, disposable barriers, or both combining various features can be readily envisioned. Our design may afford improvements in proceduralist mobility restrictions and emergency access to patients, though further testing is warranted to verify patient safety.[5] Improvements in control of perioperative inhalational risk may be an unexpected lasting impact of the COVID-19 pandemic, in the same way that universal precautions emerged from the HIV epidemic.

## Authors' contributions

Concept and design: TI, SH, GC
Acquisition, analysis, and interpretation of data: TI, SH
Drafting of the manuscript: TI, SH
Critical revision of the manuscript: all authors

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## Declarations of interest

The authors declare that they have no conflicts of interest.

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# Droplet evacuation strategy for simulated coughing during aerosol-generating procedures in COVID-19 patients

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**Keywords:** aerosol-generating procedure; airway management; cough; COVID-19; face mask; SARS-CoV-2; simulation; tracheal intubation

Editor—We read with interest the correspondences by Cubillos and colleagues[1] and Au Yong and Chen[2] describing two different barrier enclosure designs that attempt to reduce the exposure risk of aerosolised severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in healthcare providers performing aerosol-generating medical procedures. Gould and colleagues[3] questioned the merit of these enclosure devices that increased the difficulty in managing the airway and lacked any mechanism to safely remove or clean the barrier enclosures without dispersing high concentrations of aerosolised SARS-CoV-2.

Based on industrial local exhaust ventilation systems that effectively evacuate hazardous particulate matter away from workers in occupations such as surgery,[4] a similar evacuation system was recently described.[5] A commercially available, disposable adult size oxygen face tent was repurposed and connected to suction to form an aerosol evacuation system. This aerosol evacuation system showed qualitative effectiveness in removing a continuous stream of visible aerosolised saline droplets generated during simulated passive breathing. However, tracheal extubation is a different challenge for healthcare providers as coughing occurs in ~40%[6] of patients undergoing extubation.

We therefore sampled surrounding air particle concentrations in both simulated passive breathing and coughing scenarios. As shown in Fig 1 and supplementary online video, the same commercially available disposable oxygen face tent was adapted (Salters face tent; Salter Labs, Arvin, CA, USA) and connected to a closed biohazardous smoke evacuation system (Neptune 3, Stryker, Kalamazoo, MI, USA) with an internal high efficiency particulate air (HEPA) filter. This high-efficiency waste management system commonly found in operating rooms can capture aerosolised particles as small as 0.1 μm with 99.99% efficiency with suction power up to 25 $ft^3$ $min^{-1}$ air exchange. The face tent was placed in one of two positions on an adult high-fidelity airway manikin: below the manikin's chin (chin position) or on top of the manikin's forehead (forehead position). Visible aerosolised saline was introduced into the manikin with the use of a nebuliser (Airlife Misty Max 10 disposable nebuliser; Carefusion, San Diego, CA, USA) and 8 L $min^{-1}$ of oxygen to simulate passive breathing. A forceful cough was simulated by a 1.8-L resuscitator bag (Hudson RCI, Teleflex, Wayne, PA, USA) that was rapidly emptied over 1 s with the nebulised saline through the airway of the manikin. Assuming the manikin trachea is cylindrical, the air velocity of the cough is calculated as the air volume generated per unit of time divided by the cross-sectional area of the trachea. Assuming laminar flow with a manikin tracheal diameter of 1.5 cm, air velocity of the simulated cough with rapid emptying of 1.8 L over 1 s is about 10 m $s^{-1}$ (i.e. 1.8 L $s^{-1}$ ÷ [3.14×(0.75 cm)$^2$]), which is slightly lower than the reported maximum human cough air velocity (~11.7 m $s^{-1}$).[7]

Supplementary video related to this article can be found at https://doi.org/10.1016/j.bja.2020.06.009.

The particle concentration (μg $m^{-3}$) of particulate matter with diameter <2.5 μm ($PM_{2.5}$)[8] was measured using a particle counter (Digital PM2.5 Air Quality Detector, Geekcreit, Banggood, Guangzhou, China) at the level of the head of the manikin and 2 ft above the manikin's head to approximate the height of a healthcare provider performing an aerosol-generating procedure. To simulate a tracheal intubation scenario with passive breathing, measurements were taken every 30 s for 13 min with the following sequence: (a) at time 0, nebuliser activation for 3 min to simulate passive exhalation