Functional analysis of a negative pressure airborne infection isolation canopy unit for the prevention of transmission of droplets and aerosols: An experimental study

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ABSTRACT

Background and Aims: This study describes the functional analysis of a negative pressure canopy unit developed to reduce infective aerosol and droplet spread in ad-hoc wards created to handle patients suffering from infective respiratory illnesses such as those recently encountered in the COVID-19 pandemic. Methods: An experimental study was conducted to verify the functional analysis of a canopy unit for the following variables: a) Quantitative and qualitative analysis of aerosol generation, b) Efficacy of canopy as containment device and c) Aerosol clearance from canopy over a period. We describe the process in the form of a problem statement, a discussion of design considerations (including Computer Aided Design modelling and a functional analysis of the system using a variety of simulated conditions which included various experiments for the purpose of testing the safety and efficiency of the system. We also incorporated Computational Fluid Dynamics analyses to assist us in design modifications of the unit using Euler-Lagrange approach for aerosol tracking. Results: As demonstrated by the series of experiments, it was seen that the aerosol load under the testing conditions reduced significantly. The canopy unit restricted the aerosol particles which either got adhered to the canopy walls or went into recirculation inside the canopy. In experimental conditions, the fan-filter unit was able to operate at >95% efficiency. Conclusion: This device exhibited 95–99% efficiency in eliminating aerosols which would reduce the exposure of health care workers to infective aerosols, which is not only specific to severe acute respiratory syndrome coronavirus (SARS-CoV)-2, but also to other airborne transmitted diseases.

Key words: Aerosol, airborne spread, computational fluid dynamics, respiratory protective devices, respiratory tract infections, viral disease

INTRODUCTION

The need for a device to reduce aerosols in the intensive care unit (ICU) was recognised during the coronavirus disease (COVID)-19 pandemic. Health care workers (HCWs) involved in the management of the patients have been donning personal protective equipment (PPE), but the risk of contracting infection remains, since the viral load is very high in closed spaces like the ICU and the wards designated for COVID-19 patients. Patients suffering from highly
contagious airborne diseases are ideally isolated in negative pressure rooms, but a sufficient number of such infrastructure-heavy rooms may not be available in a pandemic.[4] Oxygen therapy whether administered by face masks, non-rebreathing masks (NRBM), non-invasive ventilation (NIV) and high flow nasal cannula (HFNC) or invasive mechanical ventilation (IMV) produce large amounts of viral-laden aerosols. We developed a device that scavenges the viral laden aerosols and traps them inside a high efficiency particulate air (HEPA) filter. There has been a rising number of cases of COVID-19 amongst the HCWs. As the pandemic spread, in the United States of America and the United Kingdom alone, by the first week of May 2020, there were over 250,000 HCWs affected by this disease and was responsible for 10–20% of all COVID positive patients.[5] In COVID-specific ICUs and wards, the viral load is very high and an effective scavenging system is required to make the internal environment of such a medical facility less contagious. To address the above concerns, we have developed a portable airborne infection isolation device to reduce infective aerosol spread of various sizes. The containment device is a miniature form of a negative pressure isolation room, and a final patent has been granted for this device on 03 August 2022 (patent number 402962 and application number 202021042943). The device consists of a retractable canopy unit to create a physical barrier around the patient and a fan-filter unit to scavenge and filter contaminated air. The fan-filter unit (FFU) sequesters aerosols released from the patient by applying negative pressure over the patient’s exhale cloud. We designed a prototype of a canopy and FFU with an objective to examine the safety and efficacy of the canopy FFU as a containment device for the reduction of the spread of aerosols.

METHODS

The device consists of two modules: a transparent retractable canopy unit and an FFU: to create an enclosed space around the patient, to remove and filter contaminated air, respectively. The FFU consists of: a) Prefilter – for filtering the dust particles, b) Fine filter – for particles above 5 µm and c) High-Efficiency Particulate Air (HEPA) filter – for filtering all particles from 0.3–5 µm.

Institutional ethics committee approval (ANAE/103/01/TT/2020) was obtained for the study. This experimental study was conducted at a simulated set-up over a study period of one year from January 2021 onwards. The primary objective was to determine the aerosol exposure to the HCWs. This was achieved by: a) quantitative and qualitative analysis of aerosol generation b) efficacy of canopy as containment device and c) aerosol clearance from canopy over a period of time.

The study area was the simulation lab of the Department of Anaesthesiology and critical care of our institute. The volume of the room was 34 m³. The unit under study was set up on a full body mannequin with an aerosol source created by an oxygen flow at 10 l/min flowing through a droplet generator to a nebulisation mask. This aerosol source was kept inside the canopy on the mannequin’s mouth. A particle counter was placed at various predetermined locations as per the experimental design.

Aerosol characteristics and baseline conditions: The aerosol produced ranged between 0.3 µm and 10 µm. Particle size was measured by an AeroTrak portable particle counter kept at predetermined locations as per experiments. For our experiments, we concentrated on particle sizes 0.3 µm to 10 µm. Qualitative and quantitative measurements of particles were validated by a certified testing facility. As noise generated is an important environmental concern, the noise level during the conduct of the experiments was measured by a Mextech sound level meter capable of measuring from 30 Db to 130 Db. The noise generated was 40 Db with FFU off and 80–100 Db with FFU on. The ambient temperature was 24–26°C and humidity was 72–78%. Individual experiments were carried out after obtaining baseline values which were repeated for each experiment to account for variations in ambient humidity and temperature as each of these variables significantly alter the aerosol particle count [Table 1].

RESULTS

The particulate matter exposure to the HCW was measured and the trend of the dwelling time of these particles in the vicinity of the aerosol-generating source was analysed. The particles of concern are from 0.3 µm to 5.0 µm, which makes a disease airborne.

Experiment 1 was carried out to find out the efficiency of the FFU by placing the particle counter inside the canopy and at the exit of the FFU [Table 1]. There was a continuous reduction in aerosol particles of
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all sizes [Figure 1]. This reduction was present both during intermittent and continuous aerosol generating procedures (AGPs). The filtration efficiency was more than 99% and about 100 percentile reduction in aerosol particles of all sizes took place within 5 minutes. The aerosol clearance effect for an intermittent and continuous aerosol generation was carried out in experiments 2 and 3, respectively. In both these experiments, the particle counter was kept inside the canopy. It was noted that when the nebuliser was kept on and there was no scavenging by FFU [both in experiments 2 and 3], there was an increase in the particle count (0.3–3 µm) as expected. There was a paradoxical decrease in particles of size 5 µm and 10 µm [Figures 1b and 2a]. This was due to the Coalescence Effect, which may be defined as the process when smaller aerosol particles get together to form larger particles due to cohesion. Due to this phenomenon, there was an abrupt decrease in the 5 and 10 µm particles as they adhered to the canopy and reduced the total aerosol load.

To assess whether just the canopy without the fan and suction gave protection to the HCW, experiment 4 was

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**Results:**

(A) Non-continuous aerosol generating procedures (30 seconds)

(B) Continuous aerosol generating procedures

![Image](image.png)

**Figure 1:** a) Experiment 1: Filtration efficiency test (FET) b) Experiment 2 – Aerosol clearance effect

**Table 1: Layout of experiments**

| Experiment No. | Testing parameter | Clinical Scenario | Particle counter location |
|---------------|-------------------|-------------------|--------------------------|
| 1             | Filtration Efficiency | Non-continuous AGPs | Inside Canopy (Upstream) and at the Vent (Downstream) |
| 2             | Aerosol Clearance effect | Continuous AGPs | Inside Canopy (Upstream) and at the Vent (Downstream) |
| 3             | Aerosol Clearance effect (long term) | Continuous AGPS | Inside Canopy |
| 4             | Physical barrier effect | Continuous AGPs | Outside canopy: HCW position |
| 5             | Combined effect (Clearance + Physical Barrier) | Continuous AGPs | Outside canopy: HCW position |
| 6             | Exposure to HCW | Continuous AGPs | Outside canopy: HCW position with window open |

AGPs - Aerosol generating procedures; HCW - Health care worker. Experiment 1: Assess the safety of the device. Experiments 2-6: Assess the efficacy of the device.
carried out [Figure 2b]. Here, the particle counter was placed outside the canopy near the HCW position. It was seen that as the canopy was retracted (off position) the exposure to the aerosols for the HCW increased. It was seen that the exposure of all the particle sizes increased from 30% to 50%.

Experiment 5 was carried out to assess the full functionality of our device [Figure 3a]. The canopy was deployed and the FFU was put on. Aerosol generation was continually maintained by the nebuliser. It was noted that in the first 10 minutes, the aerosol counts increased, though the exposure to the HCW was reduced owing to the physical barrier of the canopy. After 15 minutes, the FFU was switched on. The clearance effect of the FFU was ranging between 79% and 93%. This reduction was sustained for 90 minutes after which the experiment was terminated.

Experiment 6 illustrated the exposure of HCW to aerosols when the backside access window is opened for instance when performing suctioning or intubation. With the FFU off, the HCW was exposed to a greater number of aerosols. When the FFU was switched on, even with the back window open, a significant drop in the aerosol count was noted [Figure 3b].

A Computational Fluid Dynamics (CFD) study was carried out to optimise the flow rate of FFU. CFD studies suggested appropriate design modifications in the canopy unit as by adding of the diffuser case [Figure 4] that would make the air flow more streamlined and help to improve the scavenging capability of the FFU. The prototype design was developed by means of Computer Aided Design (CAD) model before fabrication [Figure 5a].

Results of CFD analysis: CFD study was carried out to modify the existing design of the device [Figures 4 and 5]. Given the speed of the fan in the simulated experimental settings, approximately 60% of the mass flow rate left the enclosure through the suction outlet, 25% recirculated in the canopy enclosure and 15% adhered to the canopy walls [Figures 5b and c].

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**Figure 2:** a) Experiment 3- Canopy clearance effect b) Experiment 4 – Physical barrier effect

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DISCUSSION

‘Aerosols’ refer to particles in suspension in gas. They are classified as follows: a) Small particles of <5–10 µm diameter, follow airflow streamlines and are capable of short- and long-range transmission; b) ‘Intermediate particles’ of diameters 10–20 µm; c) Large droplets of diameters >20 µm. The rapid desiccation of exhaled air produces minute particles that are also laden with viruses. They are known as ‘droplet nuclei’. According to the ‘Guidelines for the classification and design of isolation rooms in health care facilities’, the isolation rooms have been classified into four subtypes: a) S Class – Standard room b) N Class – Negative Pressure room c) P Class – Positive pressure room and d) A Class – Alternating pressure room.[7-9]

SARS-CoV-2 has a proven aerosol transmission which is more pronounced in closed spaces. Various devices for limiting the aerosol exposure to HCWs have been researched globally. Matava et al.[10] conducted an experimental study using a single clear plastic drape applied over the head and endotracheal tube and simulated cough while extubating. It was demonstrated that a single layer of plastic cover prevented the aerosols and droplets from spraying, but using three clear plastic sheets reduced the contamination to the surroundings to a great extent. Low fidelity design and use of large particle size were limitations of this study. A barrier enclosure or ‘aerosol box’ made of a transparent plastic cube that covers the patient’s head with two circular ports for the clinician’s hands to perform the airway procedure resulted in contamination of only the inner surface of the box, the gloves and the forearms of the person performing laryngoscopy.[11] Venketeswaran et al.[12] compared the time taken for intubation (TTI) with and without the aerosol box and found no significant increase in time difference in either scenario.

A Box for Aerosol and Droplet Guarding and Evacuation in Respiratory Infection (BADGER) was developed to contain the spread of droplets and aerosol...
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Quantitative and qualitative assessments demonstrated the ability of BADGER to act as an additional barrier for healthcare providers treating patients suffering from COVID-19. The National Institute for Occupational Safety and Health (NIOSH) developed the Ventilated Headboard. This device consists of a lightweight, sturdy and adjustable frame made of aluminium with a retractable plastic canopy. Gan CCR et al. suggested the use of a personal ventilation hood to be used as protective equipment. It consists of a ventilation hood and a suction pipe connected to a wall-mounted suction unit, allowing airflow through the HEPA filter. Adir Y et al. developed a constant flow canopy to reduce and eliminate exposure to aerosols by creating a confined area surrounding the patient in which NIV support can be safely used. The negative pressure canopy minimised risk to HCWs while administering NIV, continuous positive airway pressure or HFNC to patients with SARS-CoV-2 infection. McGain F et al. designed a system to quantify aerosol generation from respiratory procedures and the effectiveness of their elimination by a personal ventilation hood. The use of a personal ventilation hood decreased the aerosol counts by at least 98%. Seger CD et al. described a new personal containment device (PCD), a suction-assisted aerosol containment chamber with a torso drape and protective arm sleeves which provides contact, droplet and aerosol isolation while allowing intubation and cardiopulmonary resuscitation (CPR). Bassin BS et al. described a negative pressure procedural tent. Air exiting the tent passes through a HEPA filter and is then drawn out via negative pressure created by a vacuum motor prior to release into the room air. Shaw KM et al. designed a system to quantify aerosol generation from respiratory procedures and the effectiveness of their elimination by a personal ventilation hood. The reduction of colony forming units (CFUs) by high intensity HEPA filters can reduce the infectivity of the aerosolised microbes. Our experiments were carried out for extended time periods simulating real-life situations and cough was simulated by filling the cuff of an endotracheal tube with normal saline and bursting it under extra pressure. The series of filters present in the HEPA unit made the scavenging of aerosols efficient even during continuous AGPs. We were also able to demonstrate the coalescence effect that resulted in the abrupt drop in the number of larger particles when aerosol generation was continuing. Manufacturing this device is indeed economical, the cost of making a FFU is approximately INR 25,000 and a canopy unit costs INR 5000. One FFU can be attached to three canopies in its present design. Thus, the cost per bed is approximately INR 15,000. This price includes the cost of research and development which was self-financed. Our study is associated with several limitations. Several confounding factors exist during droplet spread studies, including temperature, humidity and ambient air patterns. As already researched, air temperature (within 20°C–40°C range), reduced relative humidity and lower levels of ultraviolet radiation were significantly associated with increased levels of infective droplet nuclei. Our experiments were carried out under a controlled environment in a clean and quiet room, which may not mimic the real-world environment of a patient care setting where human traffic can generate its own turbulence patterns. Mannequins were used in the experiments and so the effect of patient breathing was not factored in. The aerosol generator was a pneumatic generator with oxygen flow at 10 L/min, which delivered uncontrolled sizes of various aerosolised particles. The actual flow of oxygen/air can go up to 50–100 L/min while using NIV or HFNC. During

| SN | Zone                  | Mass-flow rate (gm/ sec) | % Distribution |
|----|----------------------|--------------------------|----------------|
| 1  | Adhesion to          |                          |                |
|    | a. Back wall         | 18.313                   | 11.912         |
|    | b. Canopy top        | 3.312                    | 1.992          |
|    | c. Canopy side       | 3.386                    | 2.086          |
|    | Total particle       |                          | 15             |
| 2  | Exh suction out       | 98.239                   | 60             |
| 3  | Recirculation of      | 43.06                    | 25             |
|    | particles in canopy   |                          |                |
|    | enclosure            |                          |                |
| 4  |HeaderText            | 186.5                    | 100            |

Figure 5: a) Computer Aided Design (CAD) model of device b) Particle tract analysis: The particle tracks represent the path followed by aerosol particles. The colour of tracks represents residence time of aerosols inside the canopy, red colour represents highest value, while blue represents lowest value of residence time c) Mass flow distribution particles.
these high aerosol producing manoeuvres, the aerosol production would be correspondingly increased.

The FFU in the current study was tested with the fan at speeds of 40 and 80 CFM. It was noticed that at higher speeds, an increase in turbulence increased the scavenging of aerosols substantially. In experimental conditions, the FFU was able to operate at > 95% efficiency, thereby, satisfying our study objective. The canopy cover is disposable, in order to prevent cross patient contamination. This device is not meant to eliminate the causative airborne microbes but to reduce the exposure to HCWs to infective aerosols which is not only specific to SARS-CoV-2, but also to other airborne transmitted diseases. It has the advantage of being portable and easily deployable in general wards and ad-hoc hospital setups during epidemics due to aerosol transmitted diseases, when the existing resources may be overwhelmed, as happened in the current pandemic.

CONCLUSION

As demonstrated by the series of experiments, our device reduced the aerosol load significantly and the FFU restricted the aerosol particles which either got adhered to the canopy walls or went into recirculation inside the canopy. This device without any doubt will reduce the noxious aerosol load in the indoor environment and definitely aid in the management of the sick building syndrome.

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Conflicts of interest

There are no conflicts of interest.

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