Effectiveness of a protective barrier for aerosol transmission control during oxygen therapy with different devices

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Abstract

This study investigated the effects of an air extraction system or a protective barrier on aerosol leakage levels using experiments conducted inside the hospital negative-pressure isolation rooms. Patient simulators were tested with five different oxygen supply devices for aerosol dispersion tests: an endotracheal tube (ET), a non-invasive ventilation (NIV) mask, high-flow nasal cannula (HFNC), a simple mask, and a non-rebreather (NR) mask. The effects of nebulized drug delivery on aerosol concentration were also investigated. The results showed that aerosol concentration was generally higher after using nebulized drug delivery than without it. For cases with HFNC and simple and NR masks, the aerosol concentrations were relatively higher, usually one to two orders of magnitude greater than those in cases with ET and NIV masks. Experiments using solely protective barrier (Case C) showed higher improvements in aerosol leakage than those using only the air extraction system (Case B); however, aerosol accumulation within the protective barrier remains an issue. In cases (Case D) using both the air extraction system and a protective barrier,
the improvements were the highest, with some values even exceeding 99%; additionally, the aerosol concentration within the protective barrier was reduced. This could potentially reduce the risk of infection for healthcare workers during clinical applications. In summary, the ability to prevent aerosol leakage is ranked as follows: Case D > Case C > Case B.

*Keywords:* Protective barrier, Aerosol transmission, Negative-pressure environment.
INTRODUCTION

Since its outbreak at the end of 2019, COVID-19 has rapidly spread worldwide, compelling countries to implement stringent preventive measures. Jimenez et al. (2022) reported that the COVID-19 virus can adhere to airborne aerosols and individuals may contract COVID-19 by inhaling these minute particles, in contrast to the larger droplets. Transmission risk assessment models by Costanzo and Flores (2022) suggested that indoor activities can trigger the dispersion and accumulation of aerosols, necessitating a reduction in indoor activities or improvements in environmental ventilation conditions. Due to the highly contagious nature of COVID-19, assisting patients with oxygen-delivery devices heightened the risk to healthcare workers due to increased aerosol dispersion. Therefore, preventing the spread of COVID-19 via droplets and aerosols into the surrounding environment was of paramount importance. Lin and Hung (2020) and Hunt et al. (2021) introduced an infection prevention box along with wall exhaust and high-efficiency particulate air (HEPA) filters. This setup was assumed to help capture aerosols exhaled by patients and prevent aerosol transmission. Nevertheless, their experimental results revealed that the aerosol box failed to completely block the transmission of droplets and aerosols. The primary issue emanated from the design of the aerosol box, which lacked complete enclosure and airtightness and allowed potential aerosol accumulation around the torso and foot regions. Consequently, the researchers suggested the supplementary implementation of exhaust equipment to address this concern.
Bazant and Bush (2021) suggested that, in addition to physical distancing, factors such as the number of individuals in a given space, mask usage, and the extent of environmental ventilation play a crucial role in virus transmission. Following an extensive review of numerous studies centered on aerosol transmission, Tang et al. (2006) presented several recommendations. These encompassed the enhancement of infection control measures to counteract aerosol transmission within hospital settings. Additionally, they proposed the regulation of airflow direction within the rooms of patients to facilitate the movement of air from healthcare workers toward patients. This approach effectively safeguards healthcare personnel against inhaling contaminated air. Numerous studies have explored the relationship between oxygen-delivery devices and aerosol (or viral) transmission. For example, Li et al. (2020) introduced the high-flow nasal cannula (HFNC) oxygen therapy, which reduced aerosol generation without increasing environmental risks. Elshof et al. (2020) suggested the possibility of viral particles being carried in droplets leaked from a patient’s mouth or nose during oxygen therapy. Leonard et al. (2020) employed computational fluid dynamics to simulate a scenario in which a patient wore a nasal cannula with a surgical mask during low-flow oxygen therapy. Their objective was to assess both the effects on the patient and the dispersion pattern of aerosols.

Several researchers and manufacturers are presently engaged in active development of an array of epidemic prevention devices customized to specifically tackle the challenges posed by COVID-
For example, Fang et al. (2020) developed an innovative, cost-effective, and readily producible protective tent that can serve as a barrier between healthcare workers and patients. The framework was covered with a transparent plastic film featuring two strategically positioned circular openings that allow healthcare workers to perform procedures with their hands inside. In a concept similar to that of Weng et al. (2021), this intubation tent design effectively restricted the diffusion of aerosols and the projection of droplets during intubation procedures. Francom et al. (2020) designed a tent with a similar concept for use during pediatric laryngoscopy and bronchoscopy procedures. This tent was constructed around the patient to minimize the dispersion of droplets and generated aerosols. Similarly, Chow et al. (2020) developed an epidemic prevention tent tailored specifically for tracheostomy procedures, allowing aerosol generating procedures (AGPs) to be performed on all categories of patients, including those suspected or confirmed to have COVID-19. This tent significantly reduced the probability of droplet contamination and virus transmission to healthcare workers or family members of the patients. Brant-Zawadzki et al. (2021) conducted a study employing exhaust equipment fortified with HEPA filters. This approach not only reduced the concentration of droplets and aerosols within the tent but also helped manage aerosol deposition, effectively addressing the issue of aerosol adherence to the protective gear of healthcare workers. Engelman et al. (2020) emphasized the need to enhance preventive measures against virus infection and transmission during AGPs, including intubation, respiratory support, and thoracic
surgeries. During these procedures, they advocated for the utilization of various protective equipment and air purification devices. Turer et al. (2021) developed an intubation box incorporating vacuum systems to actively filter air during intubation and negative-pressure isolation phases. Additional protection was achieved by employing transparent membranes to cover gaps in the front end of the casing. Their findings demonstrated that the modified intubation box effectively reduced aerosol concentration during operation and minimized the risk of virus transmission. Fox et al. (2020) designed a tent that utilized a wall exhaust to create negative pressure, effectively removing aerosols from the interior. Their results highlighted the capability of the tent to significantly mitigate the spread of aerosols, enhancing healthcare worker safety. They emphasized that the design and use of negative-pressure tents must consider various factors such as airflow control, filter selection, and operating procedures. Similarly, Rajajee et al. (2020) and Haas et al. (2021) developed negative-pressure isolation tents using vacuum pumps to establish negative-pressure environments. These tents featured a transparent plastic top section with gaps interconnected with a U-shaped ventilated base. Air within the tent was drawn through HEPA filters and released outdoors.

This study aimed to develop a new physical protective device to reduce the infection risk faced by healthcare workers during oxygen therapy procedures. To achieve this, the study commenced by designing and fabricating a prototype of the protective device. After preliminary laboratory
validation of the ability of the prototype to control the spread of pollutants, simulation experiments involving a patient simulator in the respiratory therapy drainage room at hospital were conducted. Furthermore, the potential impacts of incorporating air extraction systems on aerosol transmission control were assessed. Additionally, the behavior of aerosol dispersion in the environment during nebulized drug delivery or any assisted respiratory therapy was examined.

2 METHODS

2.1 Experimental Environment, Setup, and Process

This study was conducted in collaboration with New Taipei Municipal Tucheng Hospital, which helped provide a negative-pressure treatment room for aerosol concentration diffusion experiments. The dimensions of the treatment room were 3.6 m (length) × 3.6 m (breadth) × 2.6 m (height), with two return air vents, one air duct on the ceiling, and no return air fixtures on the walls. The aerosol concentration diffusion experiment (as shown in Fig. 1) mainly included a patient simulator, protective barrier, ventilator, air extraction system, aerosol generator, and oil-free air compressor (used to provide stable airflow to deliver aerosols into the test environment). During the experiment, an aerosol photometer (model: ATI TDA-2H; measurement range: 0.00005–120 μg L⁻¹; deviation: 1%) was used to measure aerosol concentration at three locations around the exterior of the protective barrier: at the respiratory therapist (RT) side (right side of the patient simulator), nurse staff (NS) side (left side of the patient simulator), and attending physician (AP) side (head of the
The height of the aerosol concentration sampling was the same as that of the patient’s bed (85 cm) and was 15 cm away from the protective barrier.

A physical protective barrier (cover materials: transparent polyvinylchloride, PVC; dimensions: 80 cm (length) × 80 cm (breadth) × 130 m (height); thickness: 0.5 mm; frame materials: PVC tube with a diameter of 25 mm) was developed and used in the experiment, which helped to decrease the aerosol concentration and prevent droplets from spreading to the surrounding environment, ensuring medical staff could remove ET tubes from patients and perform subsequent oxygen supply operations without removing the protective barrier. The actual application scenario and the recommendations of the medical staff of New Taipei Municipal Tucheng Hospital were considered while designing the protective barrier. These considerations included compatibility with oxygen therapy, airtightness, the ability to create a negative-pressure environment, and ease of material acquisition, cleaning, and installation. The three sides of the barrier contained two ring flanges and one natural latex glove. The length and thickness of the gloves were 78 cm and 0.8 mm, respectively; the size of the palm was 24 cm. In addition, waterproof zippers were installed on the left and right sides of the protective barrier to help medical staff during intubation and tool transfer. Furthermore, we used an additional air extraction system (physical outer dimension: 30 cm (length) × 30 cm (breadth) × 60 m (height); frame materials: 2020 aluminum alloy) to create a local negative-pressure environment inside the protective barrier to decrease aerosol concentration to <10% of the...
concentration at the source and decrease the exposure risk to medical staff during protective barrier removal. This air extraction system included a blower, four centrifugal fans (model: Delta BFB1224GH), and a HEPA filtration system. Moreover, a flow meter and a pressure gauge were installed in the system. According to the measurement data during the operation, the air extraction flow rate was 157.3 L min⁻¹ when the operating voltage and current were 16 V and 4.89 A, respectively, which created a negative-pressure environment (−0.452 Pa) inside the protective barrier. The air change rate per hour inside the protective barrier was 24.6, much higher than the recommended value (Sehulster et al., 2019).

The experimental procedure involved setting up the patient simulator, installing the protective barrier, connecting the extractor and aerosol generator (model: ATI TDA-4B), installing the aerosol concentration meter, and connecting relevant tubes. Further, the aerosol generator was turned on to release polyalphaolefin (PAO) aerosols with a mean particle size of 0.5 μm (with approximate size range of 0.05–1.0 μm). The air compressor and tubes were used to deliver PAO to the respiratory tract of the patient simulator to simulate the contaminants released by the patient during exhalation. A buffer tank was placed between the aerosol generator and the patient simulator to stabilize the aerosol supply and prevent droplet aerosols from entering the test environment. The aerosol concentration supplied was set to 23.5 μg/L, which was considered the baseline concentration for subsequent comparison of aerosol diffusion concentrations. In every experiment,
the aerosol generator continuously released PAO for 7 min: initially, stabilization of the experimental system required 2 min (not included in the record); thus, data from only the last 5 min were analyzed and considered for discussion. After the completion of each experiment, the aerosol generator was turned off; we waited for the ambient aerosol concentration to decrease to 0.005% of the baseline concentration to ensure that the environment before each experiment was the same. In addition, to prevent aerosol leakage from the experimental apparatus from affecting the subsequent results, we designed a local extraction zone containing a fan filter unit and a HEPA filter; a few devices that may leak aerosols (e.g., a buffer tank, aerosol generator, and ball valve) were placed in this zone. Additionally, two large industrial HEPA purifiers were deliberately placed within the isolation room. After each group of experiments, the two purifiers were activated to restore the aerosol concentration in the isolation room to the background level. In experiments employing the protective barrier, an air extraction system, along with a continuously operating ventilator and oxygen supply, was activated after each experiment to remove the aerosols from the patient simulator and reduce the aerosol concentration within the protective barrier to the background level. This process required approximately 30 min to complete.

2.2 Treatment Scenario and Medical Equipment

This study examined two different patient treatment scenarios: (1) patients incapable of spontaneous breathing and requiring intubation and oxygen supply and (2) patients capable of
spontaneous breathing and who were given oxygen therapy. Recently, many studies have focused on decreasing the exposure risk to the medical staff while employing the aforementioned treatment scenarios. For example, several papers used aerosol boxes (also known as intubation boxes) to decrease the risk of exposure to medical staff to the aerosols generated during the intubation and extubation of patients with COVID-19 (Brown et al., 2020; Bianco et al., 2020; Wong et al., 2021; Feldman et al., 2021). Begley et al. (2020) highlighted several problems regarding the use of intubation boxes, such as an increase in the intubation duration, thereby exposing patients to the risk of hypoxia. Intubation boxes may even damage personal protective equipment of medical staff and, therefore, increase the infection risk. Conversely, the simulation study results of Azhar et al. (2021) indicated that the intubation box significantly decreases the degree of contamination to personal protective equipment of medical staff. Herein, different scenarios were simulated. During the experiment, five common medical oxygen-delivery devices were placed on the face of the patient simulator (in combination with a ventilator) to examine aerosol diffusion. These five oxygen-delivery devices are described as follows:

1. **Type 1, Endotracheal tube (ET):** Used for assisted breathing during surgery or in patients with lung disease, thoracic trauma, or airway obstruction and protects the lungs from gastric contents or blood.
Type 2, Non-invasive ventilation (NIV) mask: Its working principle is to create positive pressure in the airway to ensure that the pressure outside the lung is greater than that inside the lung, thereby decreasing the patient’s resistance during breathing.

Type 3, High-flow nasal cannula (HFNC): HFNC can quickly provide an accurate fraction of inspired oxygen and decrease indoor air entrainment. In the experiment, the oxygen flow rate and concentration were 30 L min⁻¹ and 50%, respectively.

Type 4, Simple mask: Suitable for patients (who can breathe on their own) with chest pain, dizziness, mild bleeding, and high oxygen concentration requirements. In the experiment, a flow rate of 6 L min⁻¹ was used.

Type 5, Non-rebreather (NR) mask: A non-invasive oxygen supplementation apparatus that provides continuous oxygen flow and is used in patients capable of spontaneous breathing but requires additional oxygen. Compared with normal breathing, the NR mask can significantly increase the amount of oxygen inhaled and the oxygen supply ratio can increase to 60–91%. In the present experiment, a flow rate of 12 L min⁻¹ was used.

Two ventilators were used in this study. One was the advanced respirator (Dräger Evita® V600), commonly used for emergency treatment. In this study, Dräger Evita® V600 was only employed in the experiments using Type 1 and Type 2 oxygen-delivery devices. During the experiment, common adult usage conditions were set for the ventilator, i.e., oxygen concentration of 50%, tidal
volume of 500 mL, inspiratory time of 1 s, respiratory rate of 15 times min$^{-1}$, inspiratory flow of 32 L min$^{-1}$, and positive end-expiratory pressure of 8 mbar. The other ventilator was a simple ventilator (named MIT ventilator), designed by referencing the MIT emergency ventilator. The MIT ventilator was only employed in the experiments using Type 3, Type 4, and Type 5 oxygen-delivery devices. The ventilator structure was developed using 3D printing and included a 24-V DC motor. Arduino and a motor driver (L298n) were used to control the operating components of the motor to achieve a stable air exchange rate and respiratory flow. The values of the Dräger Evita® V600 respirator were used as a reference for setting experiment-related parameters. To simulate breathing in human lungs, we used a bag valve mask with a capacity of 1000 mL. In addition, we examined the effects of a protective barrier, an air extraction system, and nebulized drug delivery on aerosol concentration diffusion during experiments. Oxygen supply to a patient simulator could be increased by an additional 6 L min$^{-1}$ for experiments with nebulized drug delivery (i.e., nebulization inhalation therapy). In this experiment, 4 mL of sodium chloride injection was used as the test medication for nebulized drug delivery.

A total of 40 experiments were conducted under varying conditions. The cases were primarily named based on whether a protective barrier or an air extraction system was used:

**Case A**: Neither a protective barrier nor an air extraction system was used.

**Case B**: No protective barrier but an air extraction system was used.
Case C: No air extraction system but a protective barrier was used.

Case D: Both a protective barrier and an air extraction system were used.

Each of the above four cases underwent further testing with five different types of medical oxygen delivery devices. Additionally, the last letter in the case name (either E or F) indicates whether nebulized drug delivery was used: E denotes no usage and F denotes usage. Based on the naming conventions, below are two examples to facilitate easier understanding for the readers: the experimental conditions for Case A1-F were no protective barrier, no air extraction system, the use of the ET (Type 1) with a Dräger Evita® V600 ventilator, and nebulized drug delivery; the conditions of Case D5-E involved a protective barrier, an air extraction system, the use of the NR mask (Type 5) with an MIT ventilator, and the absence of nebulized drug delivery.

3 RESULTS AND DISCUSSION

3.1 Baseline Case (Case A)

Tables 1–5 show the average aerosol concentrations for Cases A1–A5 at various time intervals. The aerosol concentrations (%) in the tables are the relative values compared to the baseline concentration, generated from the aerosol generator. The results showed a slight increase in the average aerosol concentrations as measurement durations increased. For comparisons across different parameter conditions, unless otherwise specified, this study used the 5-min average value of aerosol concentration (hereafter referred as aerosol concentration). The tables also provide
measurement data from the different sides of the patient simulator: respiratory therapist (RT), attending physician (AP), and nursing staff (NS) sides. The effect of nebulized drug delivery on the aerosol concentration was also observed and analyzed in these experiments. Additionally, due to the additional 6 L min⁻¹ of oxygen flow during nebulized drug delivery, the aerosol concentrations were generally higher than those in non-nebulization scenarios; however, the extent of this increase varied depending on the type of the oxygen delivery device (Types 1–5) used. Overall, we observed that cases involving ET (i.e., Case A1) yielded the lowest aerosol leakage (lowest aerosol concentration), resulting in only a slight increase in the aerosol concentrations. This outcome was consistent with our expectations, as the ET was secured in the patient simulator’s trachea with an inflatable cuff to inhibit airway gas leakage. As shown in Table 1, the aerosol concentrations in Case A1 slightly increased from the environmental background level to 0.007–0.010%. Specifically, without nebulized drug delivery, the aerosol concentration at the RT side was 0.007% (Case A1-E); with nebulized drug delivery, this value increased only slightly to 0.009% (Case A1-F), with similar trends observed on the NS and AP sides. Notably, compared with the aerosol concentrations in Cases A2–A5, those in Case A1 were exceptionally low—around one to two orders of magnitude lower—and closely approximated the environmental background level. We also observed that the effect of nebulized drug delivery on aerosol concentration was relatively insignificant in Case A1, irrespective of the side of the patient simulator.
Experimental results revealed that the aerosol concentration in Case A2 was slightly higher than that of Case A1. For example, in the absence of nebulized drug delivery, aerosol concentration in Case A2 increased slightly from the environmental baseline level to a range of 0.013–0.014% (Case A2-E). Further analysis of the effect of nebulized drug delivery (Table 2) showed that aerosol concentrations on the RT side increased from 0.013% with no nebulized drug delivery (Case A2-E) to 0.076% with nebulized drug delivery (Case A2-F). Additionally, we observed that compared to that on the RT and AP sides, the increase in aerosol concentration on the NS side was more pronounced, increasing by 9.46-fold from 0.013% without nebulization to 0.123% with nebulized drug delivery. These findings indicate that the supplementary oxygen flow from nebulized drug delivery exerted a discernible effect on aerosol dispersion in Case A2.

The HFNC group is a highly representative experimental setup (Case A3) due to its widespread and frequent use in healthcare settings across various medical institutions. As indicated in Table 3, the aerosol concentration in Case A3 significantly increased from the environmental baseline level to 0.274–1.01%. After nebulized drug delivery, a notable increase was observed in the aerosol concentration. For example, the aerosol concentration on the RT side increased from 0.274% without nebulized drug delivery (Case A3-E) to 0.363% with nebulized drug delivery (Case A3-F). Similarly, the aerosol concentration on the NS side increased from 0.751% to 1.01%. Although these increases are smaller than those observed in Case A2, notably, the aerosol concentrations in
Case A3 were one to two orders of magnitude higher than those in Cases A1 and A2. This significant difference in the aerosol concentration is primarily due to the already high oxygen flow rate in HFNC and the absence of mechanisms to prevent exhaust leakage, as opposed to the features present in Cases A1 and A2, i.e., the ET's inflatable cuff in Case A1 and the well-sealed NIV mask in Case A2.

Experimental results presented in Table 4 indicate that the aerosol concentrations in Case A4 on all three sides of the patient simulator were significantly higher than those in Case A3. These concentrations increased from the background level to a range of 0.404–2.42%, nearly doubling the levels observed in Case A3. We assume that this increase is because of the less effective airtightness of the disposable simple mask used in Case A4, which featured two small circular openings and was secured only with standard elastic straps, leading to increased aerosol leakage. Visible aerosol leakage from these openings was observed during the experiment. Specifically, the aerosol concentrations on the RT side reached 0.404% (Case A4-E) and 0.497% (Case A4-F), respectively. Additionally, compared to the RT and AP sides, the NS side exhibited the most significant increase in aerosol concentration, particularly following the application of nebulized drug delivery (a trend also observed from the results of Cases A2 and A3). For example, aerosol concentrations on the NS side surged from 1.31% (Case A4-E) to 2.42% (Case A4-F). Notably,
this was the largest concentration difference observed across all experimental conditions from Case A1 to Case A5.

The results of aerosol concentration for Case A5 were roughly the same as those for Case A4, as shown in Table 5. Aerosol concentrations in Case A5 substantially increased from the environmental background level to a range of 0.251–2.28%, values that are significantly higher than those observed for Case A3. Such outcomes were anticipated, given that the NR mask used in Case A5 and the simple mask used in Case A4 were fundamentally the same, both with concerns of poor airtightness and aerosol leakage. According to the data shown in Table 5, the aerosol concentration on the RT side slightly decreased from 0.265% (Case A5-E) to 0.251% (Case A5-F). Similar trends were observed for both the AP and NS sides; specifically, the aerosol concentration on the AP side declined from 0.373% (Case A5-E) to 0.284% (Case A5-F) and that on the NS side declined from 2.28% (Case A5-E) to 2.12% (Case A5-F). These data suggest that under the conditions of Case A5, the use of nebulized drug delivery might have reduced (or almost maintained) the extent of aerosol dispersion, a finding in stark contrast to those from Cases A1–A4. We hypothesize that this phenomenon was attributable to the additional check valve installed for the NR mask in Case A5 to regulate oxygen flow and prevent backflow.

Based on the experimental results for Case A, some preliminary conclusions were drawn. First, under the conditions of Case A, the efficacy of the five types of oxygen delivery devices in
preventing aerosol leakage, ranked from the highest to the lowest (or from the lowest to the highest aerosol concentration): ET (Type 1) > NIV mask (Type 2) >> HFNC (Type 3) > NR mask (Type 5) ≥ Simple mask (Type 4). The aerosol concentrations when using ET and NIV masks were approximately one to two orders of magnitude lower than those recorded for the other three devices. Furthermore, when nebulized drug delivery was incorporated, the extent of aerosol leakage generally exhibited an increasing trend, except in cases involving the use of the NR mask. Importantly, the experimental environment for Case A did not include a protective barrier or an air extraction system. Therefore, the results of Case A will serve as baseline values for reference when discussing subsequent cases (namely Cases B, C, and D).

3.2 Effect of Air Extraction System (Case B)

The detailed results of aerosol concentrations in Cases B1–B5 are shown in Table 6. Overall, in Case B, the efficacy in preventing aerosol leakage, ranked from the highest to the lowest: ET (Type 1) > NIV mask (Type 2) >> HFNC (Type 3) > Simple mask (Type 4) ≈ NR mask (Type 5). This order closely resembles that of Case A. A further comparison between Cases A and B revealed that, in the context of ET where aerosol leakage was minimal, the addition of an air extraction system had a very limited effect on aerosol concentration. For example, data from Tables 1 and 6 indicate that, without the use of nebulized drug delivery, the aerosol concentration on the RT side decreased from 0.007% in Case A1-E to 0.006% in Case B1-E. When nebulized drug delivery was employed,
the aerosol concentrations of both Cases A1-F and B1-F were 0.009%. We conclude that this was primarily because the aerosol concentrations with the use of ET were already close to the environmental background level; thus, the effect of an added air extraction system (i.e., Case B1) on the changes in the aerosol concentration was limited. In other words, when aerosol leakage was exceptionally low or nearly non-existent and no other stringent concentration limits were in place, additional aerosol leakage prevention devices or mechanisms may not have been necessary.

The experimental results for Case B2 closely resembled those of Case B1. Aerosol leakage with an NIV mask was only marginally higher than that with ET. The effect of incorporating an air extraction system was more significant when nebulized drug delivery was not used. For example, without nebulized drug delivery, the aerosol concentration on the RT side dropped from 0.013% in Case A2-E to 0.009% in Case B2-E, with a 30.7% reduction. With nebulized drug delivery, the concentration declined from 0.076% in Case A2-F to 0.075% in Case B2-F, showing a 1.3% reduction. Despite the inclusion of an air extraction system in Case B2, its effect on the aerosol concentration was not significant, particularly when compared to the subsequent Cases B3–B5. This was primarily because the aerosol concentration in Case B2 was relatively low and the air extraction system operated in an open environment, offering only localized air extraction and not effectively removing low-concentration aerosols.
The experimental results for Case B3 indicated that the aerosol concentration ranges for Cases B3-E and B3-F were 0.193–0.349% and 0.283–0.505%, respectively. These values were consistent with those in Case A3 and were significantly higher than those in Cases B1 and B2. Similar to Cases B1 and B2, the influence of the air extraction system on aerosol leakage was more pronounced when nebulized drug delivery was not used. As indicated in Tables 3 and 6, without nebulized drug delivery, the aerosol concentration on the RT side dropped from 0.274% in Case A3-E to 0.193% in Case B3-E, indicating a 29.6% reduction. With nebulized drug delivery, the concentration decreased from 0.363% in Case A3-F to 0.325% in Case B3-F, a reduction as low as 10.5%. Based on these results, we concluded that even in HFNC cases with significantly higher aerosol leakage, the addition of an air extraction system exhibited limitations in mitigating aerosol leakage. Therefore, this study proceeded to include the use of the protective barrier for examining aerosol leakage, which are the related subsequent Cases C and D.

Table 6 shows that in Case B4, in which a simple mask was used, aerosol leakage substantially decreased after the addition of an air extraction system, particularly when nebulized drug delivery was used. This is markedly different from the results in Cases B1–B3. As described previously, in Cases B1–B3, the reduction in aerosol leakage after incorporating an air extraction system was significant only when nebulized drug delivery was not used. According to the results of Case B4, without nebulized drug delivery, the aerosol concentration on the RT side decreased from 0.404%
in Case A4-E to 0.258% in Case B4-E, showing a reduction of 36.1%. However, with nebulized drug delivery, the concentration dramatically decreased from 0.497% in Case A4-F to 0.106% in Case B4-F, showing a reduction as high as 78.7%. Similarly, the aerosol leakage levels on both the AP and NS sides showed significant improvements. For example, the aerosol concentration on the AP side decreased from 0.505% and 0.524% in Cases A4-E and Case A4-F to 0.366% and 0.121% in Cases B4-E and Case B4-F, showing reductions of 27.5% and 76.9%, respectively. We assume that these phenomena are due to the poor sealing capabilities of the simple mask used in this study, resulting in higher surrounding aerosol concentrations. Thus, the addition of an extra air extraction system in Case B4 made it relatively easier to reduce the aerosol concentration compared to Case A4, yielding a higher percentage of reduction in aerosol concentration.

Overall, the experimental results and the related concentration changes of Case B5 were highly similar to those of Case B4. Specifically, the aerosol concentrations on the RT, AP, and NS sides were 0.175–0.177%, 0.194–0.225%, and 1.02–1.10%, respectively. Additionally, compared to the results of Case A5, the reduction percentage of aerosol concentration ranged from 30.4% to 55.4%, which was significantly higher than those in Cases B1–B3 yet slightly lower than that in Case B4. Further analysis comparing Case A (the baseline case) with Case B allowed for the assessment of the effect of the air extraction system on aerosol leakage. First, we defined the improvement rate (IR) as follows: $\text{IR} = \left[1 - \frac{\text{results of studied case}}{\text{results of Case A}}\right] \times 100\%$. Essentially, the
IR and percentage reduction of aerosol concentration discussed earlier were the same. As shown in Fig. 2, Case B exhibited varying levels of improvement in aerosol leakage. We classified the results into three categories (low, medium, and high) based on the maximum improvement rate (IR$_{max}$): $50% \geq IR_{max} > 50% < IR_{max} < 75%$, and $IR_{max} \geq 75%$, indicated by different colors (blue, green, and red, respectively). Additionally, as IR calculations depended on distinct measurement locations, the IR for each case in Fig. 2 spanned a certain range. For example, the IR for Case B2-F was between 0.9% and 30.2% and that for Case B4-E was between 27.5% and 50.1%. A broader numerical range indicated a wider distribution of IRs across various locations (RT, AP, and NS sides), suggesting a relatively unstable aerosol concentration in the system environment. For ET and NIV masks, which had relatively lower aerosol concentrations, the IRs were also relatively low—15.8% (Case B1-E) and 33.9% (Case B2-E), respectively. However, in cases in which aerosol concentrations were significantly elevated (such as in the cases with HFNC, a simple mask, and an NR mask), the IR upon the implementation of an air extraction system exceeded 50.0%. Specifically, the IRs reached 53.5% (Case B3-E), 78.6% (Case B4-F), and 55.4% (Case B5-E). In summary, under the experimental conditions of Case B, the IRs in descending order were as follows: simple mask (Type 4) > NR mask (Type 5) > HFNC (Type 3) >> NIV mask (Type 2) > ET (Type 1).

3.3 Effect of the Protective Barrier (Case C)
The experimental results for Cases C1–C5 are detailed in Table 7. First, under the experimental conditions of Case C, the ability to prevent aerosol leakage, in decreasing order, was ET (Type 1) > NIV mask (Type 2) >> HFNC (Type 3) > NR mask (Type 5) ≈ simple mask (Type 4). This closely resembles the results of Cases A and B. Specifically, only the ranking of the simple mask and NR mask exhibited a minor difference. Compared with the results of Case A, the aerosol concentrations at various measurement locations around the environment decreased following the addition of the protective barrier. Moreover, the experimental data indicated that the aerosol concentration in Case C1-E was 0.005%, matching the background value and indicating minimal aerosol leakage. For Cases C1-F, only a very minor amount of aerosol leakage was observed, with a concentration range of only 0.007–0.008%. Further comparisons with the reference values of Case A revealed that without nebulized drug delivery, the aerosol concentration on the RT side dropped from 0.007% in Case A1-E to 0.005% in Case C1-E. With nebulized drug delivery, the concentration decreased from 0.009% in Case A1-F to 0.008% in Case C1-F. These reductions were more substantial than those observed in Case B1, indicating that the use of a protective barrier was more effective than the extraction system alone in preventing the spread of aerosols. When an NIV mask was used, the aerosol concentrations were only marginally higher than those observed in the cases with an ET, ranging from 0.006–0.007% (Case C2-E) to 0.026–0.028% (Case C2-F). Compared with that of Case A2, the range of reduction in aerosol concentration varied between
43.1–57.8% (Case C2-E) and 56.1–78.9% (Case C2-F), values that were also notably higher than those in Case B2.

As previously stated in the results of Cases A and B, the aerosol concentrations for HFNC, simple mask, and NR mask were generally one to two orders of magnitude higher than those for ET (or NIV mask). However, the aerosol concentrations in Cases C3–C5 were only slightly elevated compared to those of Cases C1 and C2 and the values remained within a narrow range, indicating that the aerosol concentration in the surrounding environment of the protective barrier was relatively stable. For example, the concentration ranges for Cases C3, C4, and C5 were 0.025–0.048%, 0.042–0.072%, and 0.032–0.057%, respectively. Moreover, compared with Cases A3–A5, the reduction in aerosol concentration in Cases C3–C5 ranged from 86.1% to 95.4%, 85.5% to 97.7%, and 78.5% to 98.3%, respectively, with the maximum reduction exceeding 95%. These observations could also be verified by the IR in aerosol leakage as presented in Fig. 3. Additionally, compared to Case B (as depicted in Fig. 2), a substantial increase was observed in the rate of improvement in aerosol leakage in Case C. This reaffirmed that the use of the protective barrier alone had a significant preventive effect on aerosol leakage, thereby reducing the risk of infection for healthcare workers. In summary, under the experimental conditions of Case C, the ranking of improvement rates from high to low was as follows: simple mask (Type 4) ≥ NR mask (Type 5) ≥ HFNC (Type 3) >> NIV mask (Type 2) > ET (Type 1).
However, within the protective barrier (where the patient simulator was located), the aerosol concentration tended to accumulate and continue to rise due to aerosol diffusion during the experimental process, especially when using nebulized drug delivery. The experimental results showed that the internal aerosol concentrations after 5 min in Cases C1-F, C2-F, C3-F, C4-F, and C5-F were 0.024%, 7.04%, 30.8%, 29.5%, and 26.2%, respectively. We observed that in the Case C1-F with ET, the internal aerosol concentration was considerably lower than those in other cases by two to three orders of magnitude due to its initially very low aerosol leakage (as shown in Table 7). For cases initially having higher aerosol leakage (i.e., HFNC, simple mask, and NR mask, as indicated by the results of Cases A and B), the protective barrier prevented aerosol leakage into the external environment but resulted in substantial internal accumulation within the protective barrier, with concentrations reaching over 30%. Therefore, to further remove accumulated aerosols within the protective barrier and minimize exposure risk when healthcare workers needed to open the mask, based on the results of Case B, we assumed that adding an air extraction system to reduce internal aerosol concentrations was an economical and effective method. This was further explored in Case D as discussed in the subsequent sections.

3.4 Combined Effects of the Air Extraction System and a Protective Barrier (Case D)

The experimental results for Cases D1–D5 are shown in Table 8. First, in Case D, the ability to prevent aerosol leakage, ranked from high to low: ET (Type 1) > NIV mask (Type 2) > simple
mask (Type 4) > HFNC (Type 3) ≈ NR mask (Type 5). Except for the ET and NIV masks, the rankings for the other three types were markedly different from Cases A, B, and C. The results showed that the aerosol concentrations were generally lower in all cases and were largely within the same order of magnitude. For example, all aerosol concentrations were only between 0.004% and 0.013% and thus relatively stable and the ratio of the highest to the lowest values was merely 3.06. Even under conditions using nebulized drug delivery, the aerosol concentrations remained very low, with negligible variation between different cases. This clearly illustrated that using a protective barrier in combination with an air extraction system was highly effective in preventing aerosol leakage. For example, the aerosol concentrations in Cases D1 and D2 were 0.004–0.006% and 0.005–0.007%, respectively—nearly the background level. Compared to the results in Case A, the percentage reduction in aerosol concentration in the absence of nebulized drug delivery was 33.3–37.3% (Case D1-E) and 56.5–61.5% (Case D2-E); with nebulized drug delivery, the reduction was 38.1–48.3% (Case D1-F) and 90.9–94.6% (Case D2-F). Similarly, compared to that in Case A, the percentage reduction in Cases D3–D5 was also extremely high, reaching up to 95.7–98.9% (Case D3), 97.6–99.5% (Case D4), and 95.1–99.5% (Case D5).

This phenomenon was strongly supported by the IRs for aerosol leakage presented in Fig. 4 for Case D. Overall, under the experimental conditions of Case D, the IRs, ranked from high to low: simple mask (Type 4) > HFNC (Type 3) ≈ NR mask (Type 5) >> NIV mask (Type 2) > ET (Type
1). These rankings were similar to those of Case C, with the difference being that the values for IRs in Case D were more densely distributed. For example, the improvement rate ranges for Cases C4-E and C5-E were 86.0–96.5% and 78.5–98.0% whereas those for Cases D4-E and D5-E were 98.0–99.2% and 95.1–99.5%, respectively. Notably, the IRs shown in Fig. 4 represent the combined effects of both the protective mask and the air extraction system. By further comparing the results of Case D to those of Case B, the effect of using a protective mask on IRs when an air extraction system was used could be evaluated (as shown in Fig. 5). Similarly, by comparing the results of Case D to those of Case C, the effect of using an extraction system on IRs was determined when a protective mask was used (as shown in Fig. 6). Upon further comparison of Fig. 5 with Fig. 6, IR achieved by adding a protective mask was observed to be significantly higher than that achieved using only an air extraction system. Additionally, the experimental results showed that the distribution of IR data in Fig. 5 was similar to the results shown in Fig. 4; the only difference was that the range of values in Fig. 5 was slightly more broadly distributed.

Regarding the issue of aerosol accumulation within the protective barrier, improvements were observed in Case D compared to Case C. Specifically, the aerosol concentrations inside the protective barrier for Cases D1-F, D2-F, D3-F, D4-F, and Cases D5-F with nebulized drug delivery were 0.018%, 1.40%, 12.3%, 14.9%, and 7.53%, respectively. Compared to the results of Case C, the percentage reductions in the aerosol concentrations within the protective barrier were 24.1%,
80.1%, 60.1%, 49.6%, and 71.3%, respectively. While it is generally unrealistic to completely avoid aerosol accumulation inside the protective barrier, achieving a high percentage reduction in aerosol concentration through control of the mechanical air extraction system parameters is a viable method. For example, increasing the flow rate of the extraction system improved the negative pressure within the protective barrier, which might have reduced both the extent of aerosol spread into the environment and the accumulation of aerosols within the barrier.

4 CONCLUSIONS

We investigated the effect of the air extraction system and a protective barrier on the aerosol leakage levels and conducted related experiments inside hospital negative-pressure isolation rooms. Patient simulators were tested with five different oxygen supply devices for aerosol dispersion tests: ET, NIV mask, HFNC, simple mask, and NR mask. The study also examined the effect of nebulized drug delivery on aerosol concentration. Based on the experimental results, the following conclusions were drawn:

(1) The aerosol concentration was generally higher after using nebulized drug delivery than without it; however, the increase varied with the use of different oxygen supply devices.

(2) In cases involving ET and NIV masks, the aerosol concentrations were relatively low, with some results even close to environmental background levels. For cases with HFNC, a simple mask, and an NR mask, the aerosol concentrations were relatively higher, usually one to two
orders of magnitude greater than those in cases with ET and NIV masks. Generally, the higher the aerosol concentration, the greater the improvement in aerosol leakage.

(3) In experiments using only the air extraction system (i.e., Case B), all cases showed a reduction in aerosol leakage. For cases with ET and NIV masks, the improvement ranged from 0% to 33.9%. For cases with high aerosol leakage such as HFNC, simple mask, and NR mask, the improvement ranged between 10.5% and 78.6%.

(4) Experiments using only the protective barrier (i.e., Case C) showed much higher improvements in aerosol leakage than those using only the air extraction system. In cases with ET and NIV masks, the improvement ranged from 15.7% to 78.9%. For HFNC, simple mask, and NR mask, the improvement ranged from 78.5% to 98.3%.

(5) In cases using both the air extraction system and the protective barrier (i.e., Case D), the IRs were the highest, with some values even exceeding 99%. This could potentially reduce the risk of infection for healthcare workers during clinical applications. For cases of ET and NIV masks, the improvement ranged from 33.3% to 94.6%. For HFNC, simple mask, and NR mask, the improvement ranged from 95.1% to 99.5%. Additionally, the aerosol concentration within the protective barrier was also reduced.

(6) In summary, the ability to prevent aerosol leakage is ranked as follows: Case D > Case C > Case B. Additionally, increasing the flow of air extraction system to improve negative
pressure within the protective barrier would reduce both external aerosol dispersion and internal aerosol accumulation.

The limitation of this study was that it was not easy to obtain the real surgical environment; therefore, a simplified method was used to study the pollutant blocking performance for epidemic prevention. Based on the present results, the airtightness of the epidemic prevention barrier, the hospital bed, and the patient's body were observed to greatly affect the difficulty of establishing the pressure difference between the inside and outside of the epidemic prevention barrier. In addition, the patient simulator used in this experiment did not have the lower body; hence, it was easier to achieve a better air tightness. However, in the real human body, limited by the shape difference of the patient's body, a larger air flow rate is inevitably required to achieve a sufficient internal and external pressure difference to prevent pollutants from escaping from the epidemic shield. Therefore, under actual conditions, isolation, pressure control, and pollutant filtration should be achieved as much as possible to ensure a safer working environment for medical personnel.

ACKNOWLEDGMENTS

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DISCLAIMER
There are no known conflicts of interest associated with this publication which could have influenced its outcome.

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Table 1. Evolution of aerosol average concentrations of Case A1.

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<td>1 min</td>
<td>0.006%</td>
<td>0.008%</td>
<td>0.006%</td>
<td>0.008%</td>
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<tr>
<td>3 min</td>
<td>0.007%</td>
<td>0.009%</td>
<td>0.007%</td>
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<tr>
<td>5 min</td>
<td>0.007%</td>
<td>0.009%</td>
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Table 2. Evolution of aerosol average concentrations of Case A2.

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<td>Case A2-E</td>
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<td>3 min</td>
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<td>5 min</td>
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Table 3. Evolution of aerosol average concentrations of Case A3.

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<td>0.242%</td>
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<td>5 min</td>
<td>0.274%</td>
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### Table 4. Evolution of aerosol average concentrations of Case A4.

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<td>Case A4-E</td>
<td>Case A4-F</td>
<td>Case A4-E</td>
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<tr>
<td>1 min</td>
<td>0.194%</td>
<td>0.442%</td>
<td>0.176%</td>
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<tr>
<td>3 min</td>
<td>0.331%</td>
<td>0.378%</td>
<td>0.468%</td>
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<td>5 min</td>
<td>0.404%</td>
<td>0.497%</td>
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**Table 5.** Evolution of aerosol average concentrations of Case A5.

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<tr>
<td>1 min</td>
<td>0.120%</td>
<td>0.189%</td>
<td>0.152%</td>
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<tr>
<td>3 min</td>
<td>0.223%</td>
<td>0.206%</td>
<td>0.291%</td>
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<tr>
<td>5 min</td>
<td>0.265%</td>
<td>0.251%</td>
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Table 6. Five-minute-average aerosol concentrations of Case B.

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<td>E</td>
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<td>0.009%</td>
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<td>0.325%</td>
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<td>0.505%</td>
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<td>Case B4</td>
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<td>0.106%</td>
<td>0.366%</td>
<td>0.121%</td>
<td>0.653%</td>
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<tr>
<td>Case B5</td>
<td>0.177%</td>
<td>0.175%</td>
<td>0.225%</td>
<td>0.194%</td>
<td>1.02%</td>
<td>1.10%</td>
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Table 7. Five-minute-average aerosol concentrations of Case C.

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<tr>
<td></td>
<td>E</td>
<td>F</td>
<td>E</td>
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<tr>
<td>Case C1</td>
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<td>0.008%</td>
<td>0.005%</td>
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<td>Case C2</td>
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Table 8. Five-minute-average aerosol concentrations of Case D.

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<td>0.006%</td>
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<td>Case D3</td>
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<td>0.011%</td>
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<td>Case D4</td>
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<td>0.008%</td>
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<td>Case D5</td>
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Fig. 1. Schematic of the aerosol concentration diffusion experiment.

(a) Experimental setup with different oxygen-delivery devices (Types 1–5)

(b) The protective barrier
Fig. 2. Improvement rates of aerosol leakage in Case B.
Fig. 3. Improvement rates of aerosol leakage in Case C.
Fig. 4. Improvement rates of aerosol leakage in Case D compared to Case A.
Fig. 5. Improvement rates of aerosol leakage in Case D compared to Case B.
Fig. 6. Improvement rates of aerosol leakage in Case D compared to Case C.