Aerosol dispersion during various respiratory therapies: a risk assessment model of nosocomial infection to health care workers

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KEY MESSAGES

1. Substantial exposure to exhaled air occurs within 1 m from patients receiving non-invasive positive pressure ventilation, even in an isolation room with negative pressure, with far more extensive leakage and room contamination via the Image 3 facemask that requires connection to the whisper swivel exhalation port, especially at higher inspiratory pressures.
2. For non-invasive ventilation, it is advisable to choose facemasks with predictable exhaled air directions and distances through the exhalation port without addition of the whisper swivel device.
3. To avoid wider distribution of exhaled air and substantial room contamination during non-invasive ventilation, high inspiratory pressures should not be used.
4. The maximum exhaled air distances during application of jet nebuliser and oxygen via nasal cannula, Venturi mask, and the non-rebreathing mask were about 0.8 m, 0.42 m, 0.4 m, and <0.1 m, respectively.
5. More extensive exhaled air dispersion and room contamination occurs during application of a jet nebuliser to patients with more severe lung injury. Use of alternative methods to deliver bronchodilators (eg meter-dose inhaler via an aerochamber or a spacer) is advised.

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Introduction

Respiratory failure is a major complication in patients with influenza A/H5N1 infection. Many patients progress rapidly to acute respiratory distress syndrome (ARDS) and multi-organ failure, requiring intensive care support. Non-invasive positive pressure ventilation (NPPV) plays a supportive role for early ARDS/acute lung injury before resorting to invasive mechanical ventilation, although it is contra-indicated in critically ill patients with multi-organ failure and haemo-dynamic instability.[1] However, NPPV may disperse infected aerosols and lead to nosocomial transmission of influenza. Exhaled air particles can be dispersed up to 0.5 m from patients receiving NPPV using the Ultra Mirage mask (ResMed, Bella Vista, NSW, Australia).[2]

This study aimed to examine (1) the direction and dispersion distance of exhaled air particles during respiratory therapies such as the use of oxygen masks (nasal cannulae, simple masks, non-rebreathing), jet nebuliser, and NPPV via Respironics facemasks in a high-fidelity human-patient simulator (HPS), (2) the effectiveness of double-door negative pressure isolation room ventilation in minimising aerosol dispersion during these respiratory therapies, and (3) the effectiveness of double exhaust fans on the general medical ward in minimising aerosol dispersion when using a Venturi mask.

Methods

This study was conducted from February 2007 to January 2009. It received non-ionising radiation and biological/chemical safety approval by The Chinese University of Hong Kong. Except for testing the exhaled air dispersion distance from the Venturi mask on a general medical ward, the rest of the experiments were conducted in one of the 36, double-door, negative pressure (-5 Pa) isolation rooms measuring 2.8 x 4.22 x 2.4 m.

We studied the deliberate leakage from the exhalation ports of ComfortFull 2 and Image 3 masks (Respironics, Murrysville [PA], USA) and other respiratory therapies (jet nebuliser and various oxygen masks) firmly attached to a high-fidelity HPS (Medical Education Technologies, Sarasota [FL], USA). The HPS represented a 70-kg adult male sitting on a 45°-inclined hospital bed. The HPS was programmed to mimic different levels of severity of

TABLE. Maximum exhaled air dispersion distances during different respiratory therapies in the human-patient simulator (HPS) under different lung conditions

Respiratory therapy	Maximum exhaled air distance (m)
Non-invasive positive pressure ventilation	
ResMed Mirage mask (inspiratory/expiratory positive airway pressure, cmH_2O)*	
10/4	0.40
14/4	0.42
18/4	0.45
Respironics ComfortFull 2 mask (inspiratory/expiratory positive airway pressure, cmH_2O)*	
10/4	0.65
14/4	0.65
18/4	0.85
Respironics Image 3 mask plus whisper swivel exhalation valve (inspiratory/expiratory positive airway pressure, cmH_2O)*	
10/4	0.95
14/4	0.95
18/4	>0.95
Simple oxygen mask (oxygen flow, L/min)*	
4	0.20
6	0.22
8	0.30
10	0.40, >0.4 during coughing
Jet nebuliser (driven by air at 6 L/min)	
Normal lung	0.45
Mild lung injury	0.54
Severe lung injury	>0.80
Nasal cannula (oxygen flow, L/min)*	
1	0.30
1	0.25 (deflected upward when using electric blanket to mimic fever)
3	0.36
5	0.42
Venturi oxygen mask	
Normal lung	
24% oxygen	0.4
40% oxygen	0.33
Severe lung injury	
24% oxygen	0.32
40% oxygen	0.29
Non-rebreathing oxygen mask (oxygen flow, L/min)	
6, 8, 10, and 12	<0.1

* The HPS was programmed to mimic mild lung injury (lung compliance of 35 mL/cm H_2O and oxygen consumption of 300 mL/min). Tidal volume and respiratory rate were regulated so that a respiratory exchange ratio of 0.8 was maintained. Typically this was achieved with a tidal volume of 300 mL and a respiratory rate of 25 breaths/min

lung injury. Airflow was marked with intrapulmonary smoke for visualisation. A leakage jet plume was revealed by a laser-light sheet and images captured by high-definition video. Normalised exhaled air concentration in the plume was estimated from the light scattered by the smoke particles.[2-5] The normalised concentration contours were made up of data collected from at least 20 breaths. A contour value of 1 indicated a region that consisted entirely of air exhaled by the patient, where there was a very high chance of exposure to the exhaled air, such as at the mask exhaust vents. A value of 0 indicated no measurable air leakage in the region and a small chance of exposure to the exhaled air.[2-5]

Results

The exhaled air dispersion distances from various respiratory therapies are summarised in the Table.

Nasal cannula

The HPS was set in a mild lung injury mode (respiratory rate of 25/min and tidal volume of 300 mL). The dispersion distance of a low normalised concentration of exhaled smoke was 0.3 m along the sagittal plane from the mouth of the HPS at an oxygen flow rate of 1 L/min. When an electric blanket was wrapped around the HPS body to mimic fever, the exhaled plume was deflected slightly upward due to thermal buoyancy effect, and the radial distance was 0.25 m. When the oxygen flow was increased to 3 and 5 L/min without the electric blanket, the radial distance of low concentration of smoke increased to around 0.38 and 0.42 m, respectively, whereas more extensive room contamination with smoke was noted (Fig 1).

Jet nebuliser

The maximum dispersion distance of a low normalised concentration of smoke particles through the nebuliser side vent was 0.45 m lateral to the HPS at normal lung condition (oxygen consumption of 200 mL/min, lung compliance of 70 mL/cmH_2O). It increased to 0.54 m in mild lung injury (oxygen consumption of 300 mL/min, lung compliance of 35 mL/cmH2O), and beyond 0.8 m in severe lung injury (oxygen consumption of 500 mL/min, lung compliance of 10 mL/cmH2O). More extensive leakage through the side vents of the nebuliser mask was noted with more severe lung injury (Fig 2).[4]

Non-rebreathing mask

As oxygen was delivered at 6, 8, 10, and 12 L/min to the HPS with normal lung mechanics, the exhaled air dispersion distances of a low normalised concentration of smoke through the one-way exhalation valve ranged from 0.06 to 0.1 m, whereas those of a high normalised concentration of smoke

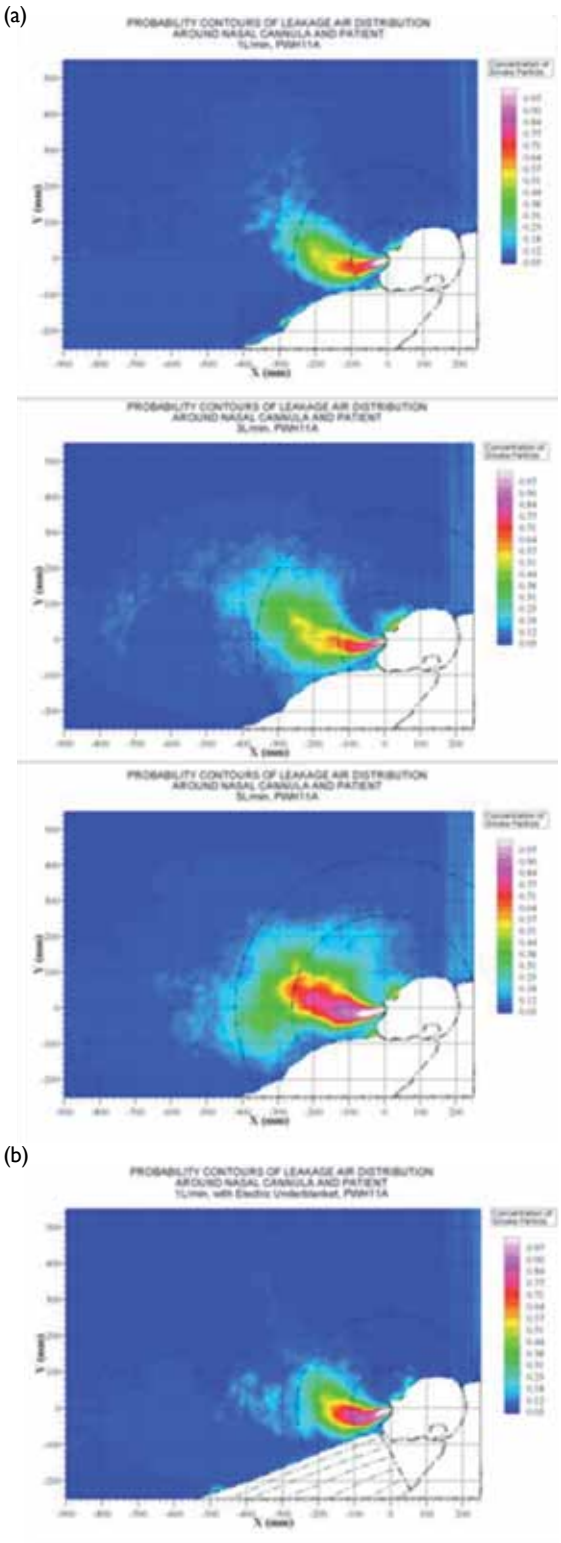

FIG 1. Exhaled air dispersion during application of oxygen via nasal cannulae

(a) When the oxygen flow was increased from 1 to 3 to 5 L/min, the radial distances of low normalised concentration of smoke were 0.3, 0.38, and 0.42 m from the human-patient simulator, respectively. (b) When an electric blanket was wrapped around the simulator body to mimic fever while receiving oxygen at 1 L/min, the exhaled plume was deflected slightly upward due to thermal buoyancy effect and the radial distance was 0.25 m.

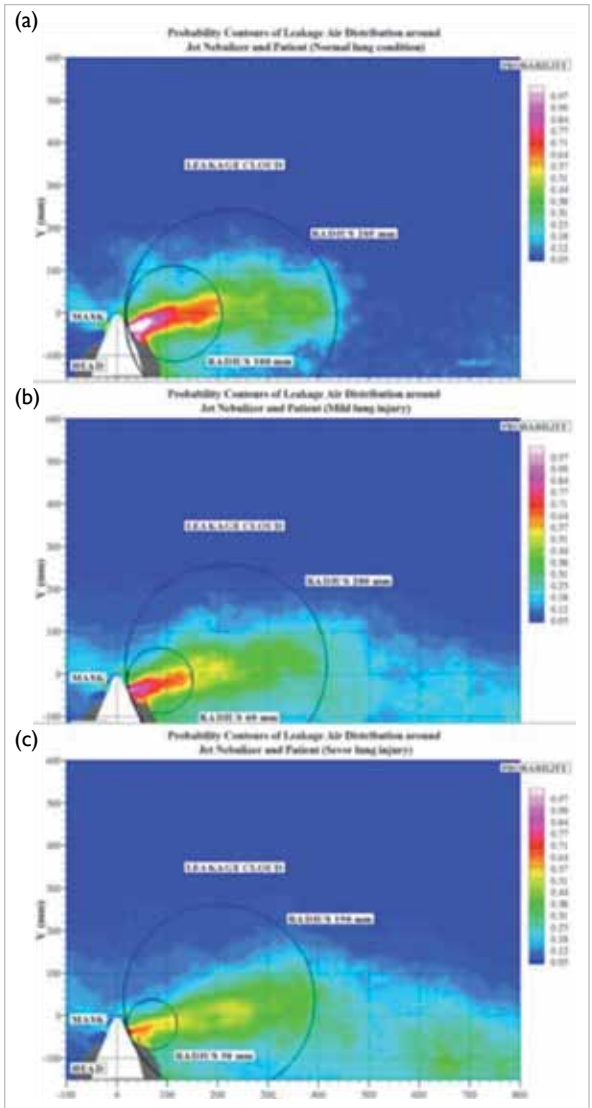

FIG 2. Exhaled air dispersion distances during application of a jet nebuliser were (a) 0.45 m, (b) 0.54 m, and (c) >0.8 m with the human-patient simulator programmed in conditions of normal lung, mild lung injury, and severe lung injury, respectively

ranged from 0.02 to 0.04 m. In severe lung injury mode, the exhaled air dispersion distances of a low normalised concentration of smoke ranged from 0.07 to 0.09 m, whereas those containing a high normalised concentration of smoke ranged from 0.02 to 0.04 m. The exhaled air distance was not proportional to the oxygen flow rate in either lung condition.

Venturi mask

In a general medical ward with double exhaust fans for room ventilation and HEPA filter, when 24% oxygen was delivered via a Venturi mask at 4 L/min to

the HPS with normal lung mechanics and then with severe lung injury, the exhaled air dispersion distances of a low normalised concentration of smoke through the exhalation port were 0.4 and 0.32 m, respectively, whereas those of a high normalised concentration of smoke were 0.17 and 0.14 m, respectively. When 40% oxygen was delivered at 8 L/min in the two lung conditions, the exhaled air dispersion distances of a low normalised concentration of smoke were 0.33 and 0.29 m, respectively, whereas those containing a high normalised concentration of smoke were the same at 0.14 m. Substantial exposure to exhaled air occurs within 0.4 m from patients receiving oxygen via a Venturi mask.

When the double exhaust fans were off, the air ventilation rates on the general medical ward dropped significantlly. The accumulative exhaled smokes filled up the ward within 5 minutes, and it was not technically feasible to measure the exhaled air dispersion distance from patients receiving oxygen via a Venturi mask.

Hudson mask with and without coughing

The HPS was programmed to breathe at a respiratory rate of 14 breaths/min and a tidal volume of 0.5 L. A jet plume of air leaked through the side vents of the simple oxygen mask to a lateral distance of 0.2, 0.22, 0.3, and 0.4 m from the sagittal plane during delivery of oxygen at 4, 6, 8, and 10 L/min, respectively. Coughing could extend the dispersion distance beyond 0.4 m. Substantial exposure to exhaled air occurs generally within 0.4 m from patients receiving supplemental oxygen via a simple mask.3

Non-invasive positive pressure ventilation

A bilevel positive airway pressure device (ResMed VPAP III ST, NSW, Australia) was used, and the expiratory positive airway pressure (EPAP) was maintained at 4 cmH_2O. When inspiratory positive airway pressure (IPAP) increased from 10 to 18 cmH_2O, the exhaled air of a low normalised concentration through the ComfortFull 2 mask increased from 0.65 to 0.85 m at a direction perpendicular to the head of the HPS along the median sagittal plane. In contrast, when an IPAP of 10 cmH_2O was applied via the Image 3 mask connected to the whisper swivel exhalation port, the exhaled air dispersed to 0.95 m towards the end of the bed along the median sagittal plane, whereas a higher IPAP resulted in wider spread of a higher concentration of smoke.[5]

The whisper swivel is an efficient exhalation device to prevent carbon dioxide rebreathing during NPPV, but it is not advisable in patients with febrile respiratory illness of unknown aetiology, especially during an influenza pandemic with high human-to-human transmission potential, for fear of major nosocomial infection. It is also important to avoid the use of higher IPAP, which could lead to wider distribution of exhaled air and substantial room contamination.[5]

Double-door negative pressure isolation room

Safe room environments depend on dilution and flow control toward extraction devices which target the exhaled air. This study confirmed the importance of maintaining adequate air ventilation rates in an isolation room—at least 12 air changes per hour—as recommended by the US Centers for Disease Control and World Health Organization. On the general medical ward, provision of double exhaust fans improved the air ventilation rates. Within isolation units, pressure differentials were essential for confining and removing exhaled air.

Discussion

In 2003, a nosocomial outbreak of SARS in our hospital was probably due to the use of a jet nebuliser for the administration of aerosolised albuterol in an index patient on a crowded medical ward. The maximum dispersion distance of exhaled air through the side vent of the jet nebuliser, driven by 6 L/min of air, was about 0.8 m lateral to the HPS.[4] The maximum exhaled air distances from patients receiving oxygen via a Hudson mask[3] and during NPPV via the ResMed mirage mask[2] were 0.4 and 0.5 m, respectively when the HPS was programmed at very mild lung injury. The maximum exhaled air distances from application of oxygen via nasal cannula, Venturi mask, and the non-rebreathing mask were 0.42, 0.4, and <0.1 m, respectively.

Our study was limited by the use of smoke particles as markers for exhaled air. The inertia and weight of larger droplets in an air-droplet two-phase flow would certainly cause them to have less horizontal dispersion than the continuous air carrier phase in which they travel due to increased inertia and drag. However, evaporation of water content in some droplets during NPPV and other respiratory therapies may produce droplet nuclei suspended in air, whereas the larger droplets fall to the ground in a trajectory pathway. As the smoke particles mark the continuous air phase, our data contours refer to exhaled air. Our results therefore represent the upper-bound estimates for the dispersion of droplets, which are expected to follow a shorter trajectory than the air jet due to gravitational effects, but they do not fully reflect the risk of droplet transmission.[2-5]

Substantial exposure to exhaled air occurred within 1 m from patients receiving NPPV in an isolation room with negative pressure via the ComfortFull 2 mask and the Image 3 mask connected to the whisper swivel exhalation port; the latter mask resulted in far more extensive leakage and

room contamination, especially at higher IPAP. The maximum exhaled air distances from application of jet nebuliser and oxygen via nasal cannula, Venturi mask, and the non-rebreathing mask were about 0.8, 0.42, 0.4, and <0.1 m, respectively. Health care workers should take adequate precautions when providing respiratory support to patients with pneumonia of unknown aetiology complicated by respiratory failure.

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References

1. Hui DS. Influenza A/H5N1 infection: other treatment options and issues. Respirology 2008;13(Suppl 1):S22-6.
2. Hui DS, Hall SD, Chan MT, et al. Noninvasive positive-pressure ventilation: an experimental model to assess air and particle dispersion. Chest 2006;130:730-40.
3. Hui DS, Hall SD, Chan MT, et al. Exhaled air dispersion during oxygen delivery via a simple oxygen mask. Chest 2007;132:540-6.
4. Hui DS, Chow BK, Chu LC, et al. Exhaled air and aerosolized droplet dispersion during application of a jet nebulizer. Chest 2009;135:648-54.
5. Hui DS, Chow BK, NG SS, et al. Exhaled air dispersion distances during noninvasive ventilation via different Respironics face masks. Chest 2009;136:998-1005.