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Risks posed by the use of oxygen therapy and non-invasive positive pressure ventilation: a pilot study

Key Messages

1. Substantial exposure to exhaled air occurs within a 0.5 m radius of patients receiving non-invasive positive pressure ventilation and a 0.4 m radius of those receiving oxygen therapy.
2. Health care workers should take protective precautions when managing patients with community-acquired pneumonia complicated by respiratory failure.

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Introduction

Community-acquired pneumonia (CAP) is a common disease with high morbidity and mortality. Patients with CAP may require various forms of respiratory support, including supplemental oxygen delivered via nasal cannulae or face masks, non-invasive positive pressure ventilation (NPPV), and invasive mechanical ventilation. There is a strong association between ventilation, air movements in buildings, and the transmission of infectious diseases such as measles, tuberculosis, chickenpox, influenza, smallpox, and SARS.[1] In patients with viral pneumonia, there is a potential risk that the respiratory therapy may generate and disperse infective aerosols, resulting in a super-spreading event. The use of a nebuliser in an overcrowded medical ward with inadequate ventilation is thought to have caused a nosocomial SARS outbreak in our hospital in 2003.[2-4]

Respiratory failure is the major complication in patients with influenza A/H5N1 infection, and many such patients progress rapidly to acute respiratory distress syndrome and multi-organ failure.[5] The US pandemic influenza plan recommends health care workers (HCW) to take precautions against airborne transmission of infection when managing patients with pandemic influenza of increased transmissibility and during procedures that may generate small aerosol particles of respiratory secretions.[6] As part of our preparation for pandemic influenza, we studied the dispersion distances of air particles during application of NPPV and oxygen therapy via standard masks attached to a high fidelity human patient simulator (HPS).

Aims and objectives

Viruses such as influenza may be spread by airborne particles and droplets. It is not known how exhaled air and particles are dispersed during the application of NPPV and oxygen therapy in clinical settings. There is no reliable marker that can be safely introduced into patients to enable such a study. Using laser visualisation techniques on a high fidelity HPS, we studied air and particle dispersion distances during the use of NPPV and oxygen therapy, via a simple oxygen mask, to the HPS.

Methods

This study was undertaken by a multidisciplinary team of investigators consisting of physicians, intensivists, anaesthetists, architects, and an aeronautical engineer. It was conducted in a quiet laboratory room measuring 7.1×8.5 m, with a height of 2.7 m. The ventilation was temporarily suspended during the experiment to avoid potentially confounding environmental factors, such as air currents.

Non-invasive positive pressure ventilation and the lung model

We studied the mask interface leakage and deliberate leakage from the exhaust holes of an oronasal mask (Ultra Mirage Medium, ResMed, Sydney, Australia) firmly attached to an HPS (HPS 6.1, Medical Education Technologies, Sarasota [FL], US). The HPS is a realistic representation of human respiration. It contains a realistic airway and a lung model that performs gas exchange, ie it removes oxygen and adds carbon dioxide to the system. The lung compliance and airway resistance also respond in a realistic manner. The HPS also produces an airflow pattern close to the in vivo human pattern, and has been used in previous studies to simulate human respiration.[7-11]

A bi-level positive airway pressure device (ResMed VPAP III ST, Sydney, Australia) was used via an oronasal mask. The inspiratory positive airway pressure (IPAP) was initially set at 10 cm H_2O, and gradually increased to 18 cm H_2O. The expiratory positive airway pressure (EPAP) was maintained at 4 cm H_2O throughout this study.[12]

Simple oxygen mask and the lung model

We studied the air particle leakage from the side vents of a simple oxygen mask (HS-3031, Hsiner, Taichung Hsien, Taiwan) applied to the HPS. Oxygen was delivered to the HPS via the simple mask at 4 L/min initially, then gradually increased to 6, 8 and 10 L/min.[13]

The lung compliance and oxygen consumption of the HPS was set to 35 mL/cm H_2O and 350 mL/min, respectively. Tidal volumes and respiratory rates were regulated so that a respiratory exchange ratio of 0.8 was maintained. This gave a tidal volume of 500 mL at a rate of 14 breaths/min, which represented a patient with a mild lung injury.[14,15] While the HPS was breathing oxygen at 6 L/min with the simple oxygen mask, coughing was produced by a short burst (2 sec, 400 L/min) of air (marked by smoke) generated by a jet ventilator (Monsoon, Acutronic Medical Systems, Baar, Switzerland) connected to the proximal trachea. This represented coughing efforts in patients with mild lung injuries.[16]

Flow visualisation

Visualisation of airflow around the interface mask was facilitated by marking air with smoke particles produced by a M-6000 smoke generator (N19, DS Electronics, Sydney, Australia).[12,13] The oil-based smoke particles (<1 µm in diameter) are known to follow the airflow pattern precisely with negligible slip.[17] The smoke was introduced to the right main bronchus of the HPS continuously. It mixed with alveolar gas, and was then exhaled through the airway. Sections of the leakage jet plume were then revealed by a thin laser light sheet created by an Nd:YVO_4 Q switched, frequency-doubled laser (OEM T20-BL 10-106Q, Spectra-Physic, USA).[12,13]

The experiments were recorded with a digital video system (3CCD, 48X zoom, 30 Hz). The laser light sheet (Green, 527 nm wavelength, TEM_{00} mode) was adjusted to encompass the largest cross-section of the entire leakage jet plume. The light sheet was initially positioned in the median sagittal plane of the HPS then shifted to the paramedian planes. This enabled investigation of the regions directly above and lateral to the mask and the patient.[12,13]

Image analysis

We estimated the normal smoke concentration of the oxygen mask leakage jet plume from the light scattered by the smoke particles.[8] This extended the laser flow visualisation and provided a useful quantitative method for understanding the range and shape of the leakage jet plumes. This technique was previously developed for turbulent two-phase, air-particle flows and has been proven as reliable as isokinetic sampling[18] or particle image velocimetry.[19]

The laser light sheet illuminated the smoke particles around the NPPV mask and the oxygen mask. The laser light scattered by the smoke particles was then collected by the video camera. In a small space, the number of smoke particles within the space (or the particle concentration) is proportional to the total scattered light intensity in the corresponding area, because the smoke particles were all the same size, or monodisperse.[17]

Image capture and frame extraction

The motion of several breathing cycles at a given oxygen flow rate setting was recorded in a computer, and individual frames extracted as grey-scale bitmaps for intensity analysis. Frames were extracted at times corresponding to the beginning of inspiration (at a given oxygen flow rate) to generate an ensemble average for the corresponding instant of the respiratory cycle. The largest spread of contours from the mask was chosen and this was found to be at approximately the mid time of the respiratory cycle.[12,13]

Results

During the application of NPPV, a jet plume of air leaked through the mask exhaust holes to a radial distance of 0.25 m from the mask when IPAP was 10 cmH_2O, with some leakage from the nasal bridge. The leakage plume exposure probability was highest about 60-80 mm lateral to the median sagittal plane of the HPS. Without nasal bridge leakage, the jet plume from the exhaust holes increased to a 0.40 m radius from the mask, whereas exposure probability was highest about 0.28 m above the patient. When IPAP was increased to 18 cm H_2O, the vertical plume extended to 0.45 m above the patient with some horizontal spreading along the ceiling.[12]

During delivery of oxygen via a simple mask at 4, 6, 8 and 10 L/min, a jet plume of air leaked through the side vents of the mask to a lateral distance of 0.2, 0.22, 0.3, and 0.4 m from the sagittal plane, respectively. Coughing could extend the dispersion distance beyond 0.4 m.[13]

Discussion

Air marked with smoke particles can be emitted through deliberate mask leakage to a radial distance of approximately 0.25 m from an oronasal mask during application of NPPV. The leakage jet plume was most significant about 60-80 mm lateral to the median sagittal plane. Despite the use of a reasonably well-fitted mask, leakage was still detected at the nasal bridge. With elimination of this nasal bridge leakage, the jet plume radial distance from the mask increased to 0.4 m, with exposure probability highest about 0.28 m above the patient and the mask. When IPAP was increased to 14 cm H_2O and then 18 cm H_2O, the vertical plume extended to 0.42 m and 0.45 m respectively above the patient, with some horizontal spreading along the ceiling.[12] These findings have important clinical implications for HCW who often nurse their patients at a close distance, especially during NPPV support for respiratory failure, at a stage when viral loads may reach peak levels. Our study emphasises the importance of medical ward design for ensuring a ventilated, aerodynamic space and the need for an architectural aerodynamics approach to minimise the risk of nosocomial infection. Air-conditioning or extraction systems need to target the circular region above the mask rather than the actual mask level.

This study simulates a worst-case scenario in order to demonstrate the maximum distribution of exhaled air. Using laser smoke visualisation methods, we showed that exhaled air dispersed at maximal distances of 0.2, 0.22, 0.3, and 0.4 m (for contours above 20%) lateral to the median sagittal line of the HPS when oxygen was delivered via a simple mask at 4, 6, 8 and 10 L/min respectively. Within these dispersal distances from the mask, the chance of exposure to the patient's exhaled air is greater than 20%. Thus within dispersal distances of 0.16, 0.17, 0.25, and 0.35 m, there was at least a 60% chance of exposure to the exhaled air at oxygen flows of 4, 6, 8, and 10 L/min respectively. Coughing increased the air dispersion distance from 0.17 m to 0.2 m when the HPS was receiving 6 L/min of oxygen with at least a 60% chance of exposure within the distance.[13] These findings have important clinical implications for HCW who often manage patients with CAP at a close distance. A case control study involving 124 medical wards in 26 hospitals in Guangzhou and Hong Kong has identified six independent risk factors for super-spreading nosocomial outbreaks of SARS. They are the minimum distance between beds <1 m, performance of resuscitation, staff working while experiencing symptoms, and SARS patients requiring oxygen therapy or NPPV. The availability of washing or changing facilities for staff was a protective factor.[20] It is important to provide adequate respiratory protection for HCW, in addition to applying standard contact and droplet precautions, in order to prevent nosocomial infections.

This study was limited by the use of smoke particles as markers for exhaled air. The inertia and weight of larger droplets would certainly cause them to have less horizontal dispersion. Nevertheless, the evaporation of water content in some droplets during NPPV or oxygen therapy may produce droplet nuclei suspended in air, whereas the larger droplets will fall to the ground in a trajectory pathway. As the smoke particles in this study mark the continuous air phase, our data contours are referring to exhaled air. Our results represent the upper boundary of estimates for the dispersion of droplets that would be expected to follow a shorter trajectory than the air jet due to gravitational effects, but not fully reflect the risk of droplet transmission. In addition, ventilation was switched off during the experiments in order to reveal the maximum distribution of exhaled air without interference by external factors. Further work is needed to assess the interaction between ward ventilation and the dispersion distances during different modes of therapy for respiratory failure. We were unable to capture the maximum dispersion distance during coughing due to limitations of the equipment. A higher speed camera with a wider laser beam is required to detect the full range of dispersion distances during manoeuvres such as coughing and sneezing.[12,13]

Conclusions

Substantial exposure to exhaled air occurs within a 0.5 m radius of patients receiving NPPV and a 0.4 m radius of those receiving oxygen therapy. Higher ventilator pressures result in a wider distribution of exhaled air. Coughing can extend the dispersion distance further.

Health care workers should be aware of the potential risks of viral transmission during application of NPPV and oxygen therapy for patients with CAP. It is advisable to follow the World Health Organization recommendation that precautions for airborne transmission be adopted in health care facilities, including placing patients with suspected and confirmed H5N1 influenza in isolation rooms with at least 12 air exchanges/hr during aerosol-generating procedures. Further studies are needed to examine the dispersion of exhaled air during common respiratory therapies in relation to the air exchange rate and airflow patterns in medical wards, and its role in the control of airborne virus infection.

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