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Airflows Around Oxygen Masks*

A Potential Source of Infection?

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Patients with respiratory infections often require the use of supplemental oxygen via oxygen masks, which, in the hospital, may become sources of aerosolized infectious pathogens. To assess this risk, a human lung model (respiration rate, 12 breaths/min) was designed to test the potential for a simple oxygen mask at a common setting (4 L/min) to disperse potentially infectious exhaled air into the surrounding area. A laser sheet was used to illuminate the exhaled air from the mask, which contained fine tracer smoke particles. An analysis of captured digital images showed that the exhaled air at the peak of simulated exhalation reached a distance of approximately 0.40 m.
(CHEST 2006; 130:822–826)

Key words: aerosol; airborne; airflow; hospital-acquired; infection; infection control; nosocomial; oxygen mask; transmission; visualization

Abbreviations: CoV = coronavirus; HPS = human patient simulator; SARS = severe acute respiratory syndrome

Patients admitted to the hospital with pneumonia often require supplemental oxygen via nasal cannula or oronasal masks. Usually, there are no additional isolation precautions taken for such patients, and they may be on an open ward with a respiratory infection, breathing with the aid of an oxygen mask that is supplying oxygen at a flow rate of up to 10 L/min. However, little is known about the airflow characteristics of such oxygen delivery devices and their ability to transmit infection by aerosol. This problem of hospital-acquired infection via infectious aerosol was highlighted in the severe acute respiratory syndrome (SARS) epidemics of 2003.[1] Many cases of SARS occurred within hospitals with infections taking place between patients and health-care workers, in some cases apparently assisted by oxygen delivery and other respiratory support devices.[1] Since then, it has been reported that SARS-coronavirus (CoV) RNA can be detected in air,[2] and in some cases airborne SARS CoV can also be grown in culture, demonstrating viability.[3] More recently, avian influenza (influenza H5N1) has led to a high mortality rate in human cases in Thailand and Vietnam.[4,5] The strongest case implicating person-to-person transmission of influenza H5N1 also occurred in a hospital setting.[6] The potential for long-range, airborne transmission for both influenza[6,7] and SARS CoV[8] has been reported. Yet, it has been difficult to demonstrate the risk of aerosol transmission of such

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This project was supported by the Research Fund for the Control of Infectious Diseases from the Health, Welfare and Food Bureau of the Hong Kong Special Administrative Region Government.

The authors have reported to the ACCP that no significant conflicts of interest exist with any companies/organizations whose products or services may be discussed in this article.

Manuscript received December 1, 2005; revision accepted February 22, 2006.

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DOI: 10.1378/chest.130.3.822

respiratory infections in the health-care environment, and there are still many serious gaps in our knowledge.[7]

In one study, using aerosolized 3% hypertonic saline solution and photographic techniques, Somogyi et al[9] demonstrated that throughout exhalation, both the nonrebreathing and Venturi-type oxygen masks channeled the exhaled gas through side vents, forming a leakage plume of exhaled gas that was directed to either side of the patient. The authors asked the volunteer to hold his breath for approximately 2 s, while the masks were fitted to his face. The volunteer then exhaled smoothly for at least 2 s, during which a series of still photographs were taken. Although the volunteer's breathing action was not physiologic in this study, the authors demonstrated that such oxygen masks could produce potentially infectious plumes from exhaled air that could be inhaled by health-care workers, visitors, and other patients.

In order to further assess the potential for oxygen masks to spread infection, we designed a human lung model with a more realistic breathing cycle. In addition, we applied an engineering-based approach to visualize and analyze the airflow images recorded on digital video during simulated respiration with a simple oxygen mask.

Materials and Methods

Human Lung Model

A high-fidelity human patient simulator (HPS) [model 6.1; Medical Education Technologies Inc; Sarasota, FL], representing a medium-sized adult man sitting on a 45°-inclined hospital bed, was fitted with a simple oxygen mask (HS-3031; Hsiner; Taichung Hsien, Taiwan). The head, neck, and internal airways of the HPS were configured to allow realistic airflow modeling in the airways and around the face. Oxygen flow was set as 4 L/min, and the simulator was programmed for a respiratory rate of 12 breaths/min and a tidal volume of 0.5 L.

Imaging and Video Capture System

The mask airflow was visualized by smoke using an M-6000 smoke generator (model N19; DS Electronics; Tempe, AZ). The generated smoke was continuously introduced to the right main bronchus of the HPS as part of the inhaled air. This design allowed the smoke to continuously mix with the alveolar gas and then to be part of the exhaled air, to allow visualization.

Initially, the smoke airflow was illuminated with a strong halogen light to reveal the full three-dimensional extent of the mask airflow and the leakage plume. Sections through the plume were then revealed by an intense laser light-sheet created by an Nd:YVO$_4$ Q-switched, frequency-doubled laser (OEM T20-BL 10–106Q; Spectra-Physics Lasers; Mountain View, CA), with custom cylindrical optics for two-dimensional laser light-sheet generation (Fig 1). This was recorded with a three charge-couple device, ×48 zoom digital video system (Sony; Tokyo, Japan) at an image rate of 30 Hz.

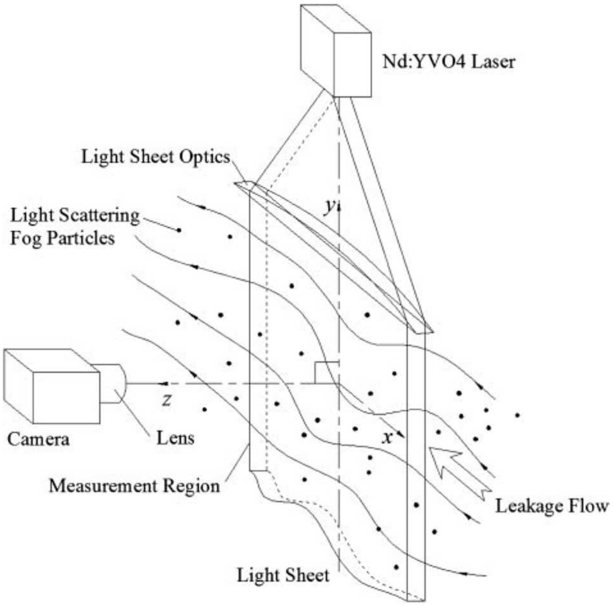

FIGURE 1. Basic arrangement of the two-dimensional laser light-sheet and camera. The digital video camera filmed from only one side of the mask, leading to an asymmetrically illuminated image record. In the final image processing, symmetry was assumed based on the symmetrical structure of the mask.

The laser light-sheet was adjusted to encompass the full leakage plume, which was previously identified from the halogen light observations and set at a thickness of approximately 1 to 2 mm. The light-sheet (green, 527-nm wavelength, transverse electromagnetic mode $_{00}$, and 2-W average power) was positioned on one side of the manikin, with the plane of the light-sheet adjusted for the mask to illuminate as much of the smoke cloud as possible. The cross-sectional plane of the leakage plume and sections through it were of interest. The laser could be run in continuous wave mode (100 mW average power), or high-frequency (350 kHz) pulsed mode for pulse intensities up to an average of 2 W. Pulse frequencies of > 1 kHz were found to be effectively continuous wave for both video and observation by eye.

Following the positioning of the laser light-sheet, the video images captured were synchronized with the respiratory cycle by starting the video capture at the exact beginning of breath exhalation. The video recording captured many simulated breath cycles, and the images corresponding to the maximum expired volume during each respiratory cycle were analyzed. Both real-time full-motion video (30 images per second) and snapshot images of the video images were analyzed.

Video Image Analysis

Full-motion video was reviewed in real-time using a movie editor (Windows Movie Maker; Microsoft; Richmond, WA), and the best images of respiration showing airflow behavior were analyzed using software that was developed for this study (Matlab 6.5). In order to obtain the clearest boundary of dissemination, image-processing techniques were applied to these images to define the edge of the visible smoke boundary from the captured digital video images (see supplementary material at www.chestnet.org). These techniques were applied to a selected video image that represented the peak of simulated exhalation during one breath cycle by the human simulator. Finally, we assumed that the smoke propagations were symmetric under the symmetric mask structure. This was observed and confirmed during the initial three-dimensional flow visualization using the halogen light. Hence, a symmetric image was constructed (Fig 2).

RESULTS

The final maximum distance traveled by the exhaled smoke plume, using this simple oxygen mask (HS-3031; Hsiner) with an oxygen flow of 4 L/min, a respiratory rate of 12 breaths/min, and a tidal volume of 0.5 L, was approximately 0.40 m (Fig 2). It was finally decided to choose the video image/footage of the most clearly illuminated smoke plume, demonstrating the maximum distance traveled at the peak of exhalation for image analysis. The reason for this was one of safety. Such a maximum distance will give added safety if it is used as a guide to the safe distance required for the prevention of hospital-acquired aerosol transmission infections. This distance was defined on the basis of the image analysis technique that was used to smooth and approximate the boundary of the visible smoke on video that had been recorded by the digital camera. The defined boundary of the smoke was based on the reflected light intensity of the smoke particles when illuminated by the laser sheet (see supplementary material for further details).

DISCUSSION

The HPS has been used in medical training, especially in anesthesia, emergency, and critical care medicine. It is also a realistic representation of human respiratory physiology. The HPS contains a realistic airway and a lung model that undergoes gas exchange (*ie*, it consumes oxygen and produces carbon dioxide). The lung compliance and airway resistance respond in a realistic manner to relevant challenges. It also produces an airflow pattern that is close to the *in vivo* human situation. A report on the use of an HPS to study complex respiratory physiology has been published previously.[10–14]

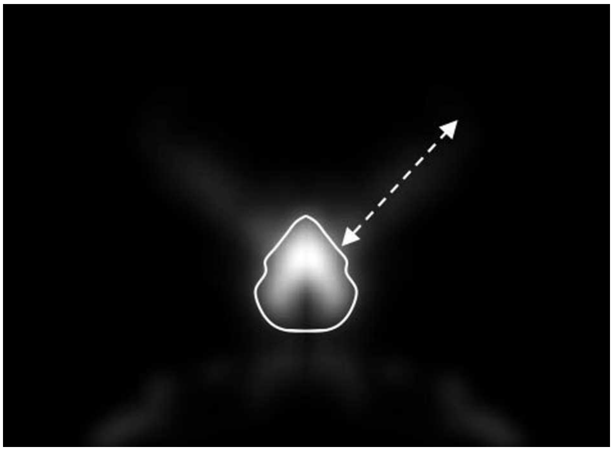

FIGURE 2. Final processed image. The symmetry has been produced by reflection in the mid-line axis to compensate for the unilateral plane laser-sheet illumination. The white outline represents the approximate position of the mask when looking vertically down on the face of the human lung model dummy. The double-headed, white, dotted arrow shows the visible extent of the smoke plume (based on a gray scale of 0 to 255). When scaled up in real dimensions, this arrow represents a real distance of approximately 0.40 m.

There have been a few studies about the production of aerosols from the use of oxygen masks. However, although their methodology was quite different, a useful comparison can still be made with the study by Somogyi et al,[9] who produced images of exhaled airflows using three different oxygen masks on a human volunteer. Their study is not directly comparable to this one mainly because the oxygen masks they used had no oxygen flow supplied. Only the volunteer's natural exhalation after brief breath holding produced the air movement. This is not a natural breathing cycle, and, in this respect, the cyclical respiration pattern in the human lung model presented here may be more realistic. Although Somogyi et al[9] showed images of the behavior of the exhaled air plume, they did not report quantitative data, such as the distance traveled by the visible air plumes shown in their images. However, a closer inspection of their Figure 1A, which illustrates a side plume of exhaled air emitted from a simple nonrebreathing oxygen mask, appears to show that it extends approximately two head diameters away from the mask. The head diameter of an adult has been reported to be approximately 13 to 16 cm.[15] Thus, the extent of the visible plume shown in their Figure 1A can be estimated to be approximately 0.30 m. Furthermore, these authors stated the following: "The spread of the exhaled gas may be greater than shown, as evaporation and reduction in density of the droplets at the margin of the plume may limit their effectiveness as markers." Although the methodology and human lung model parameters used in this study may have been somewhat different (oxygen flow, 4 L/min; respiratory rate, 12 breaths/min; tidal volume, 0.5 L), the distance traveled (0.40 m) by the exhaled smoke plume in this study seems remarkably similar.

There are some limitations that are specific to this study. Most significantly, fine smoke particles rather than droplets were used in this study. This smoke consists of submicrometer m particles that will follow the path of the air flow precisely.[16,17] Thus, the extent of spread of the smoke is representative of the airflow around the mask. This distance is derived from smoke particles that are visible enough to be analyzed from the digitally captured video images.

This will almost certainly be a lower limit approximation as there will be smoke particles traveling beyond the visible boundaries seen in these images. These particles cannot be visualized effectively because there are too few at these distances to scatter sufficient light to be easily detected on the video images.

Second, it has been estimated that droplets generated from the upper respiratory tract by, for instance, coughing, sneezing, talking, singing, and breathing, range from 0.5 to 12 μm in diameter.[18] As viral and bacterial agents range from approximately 0.020 to 100 μm in size, the size of the exhaled droplet will obviously limit the number of such infectious agents that can be carried in each droplet. The majority of naturally produced aerosol droplets are much larger than the smoke particles used in this study. Therefore, most of them will not follow the exhaled airflow perfectly, but will move relatively more slowly horizontally due to their larger size and will fall more quickly under the effects of gravity[19] and thus not travel as far as the smoke particles used in this study. However, some of the smaller droplets exhaled by a human patient may be reduced in size sufficiently by evaporation within the exhaled, oxygen-assisted airflow and remain suspended in air for considerable periods of time. These smaller particles may then more closely be represented by the smoke particles used in this study. Therefore, the boundaries of the smoke cloud indicated in Figure 2 are likely to represent an upper boundary of the distance traveled by real infectious droplets and may therefore be taken as defining a zone of potential aerosol infection with an extra margin of safety.

There is no reliable and safe marker that can be introduced into human lungs for study. The use of the human lung model here allows for only one set of parameters to be tested at one time. So, while a healthy human patient would sometimes be breathing quietly, then sometimes talking, coughing, or sneezing (when the mask may be removed), the behavior of this human lung model is unchanging. However, this study allows a baseline estimate of the distance traveled by any potentially infectious aerosols, while the patient is at rest.

Conclusion

This study effectively complements that of Somogyi et al[9] and demonstrates that patients with transmissible respiratory infections such as influenza H5N1 and SARS, who are breathing with the aid of oxygen masks, may be a potential source of aerosol-transmitted infection. These patients should, ideally, be managed in a single, isolation room, under negative pressure, though with their relatively high cost, not all health-care institutions may possess such facilities. During the SARS epidemics of 2003, health-care workers managing SARS patients found that they could protect themselves by the effective and consistent use of personal protective equipment,[20] and that the converse was also true.[21] Influenza H5N1 is likely to be a more infectious, transmissible pathogen,[22] so effective, well-informed infection control precautions will be even more important to prevent hospital-acquired infections in both health-care workers and patients.

References

1 Fowler RA, Lapinsky SE, Hallett D, et al. Critically ill patients with severe acute respiratory syndrome. JAMA 2003; 290:367–373

2 Booth TF, Kournikakis B, Bastien N, et al. Detection of airborne severe acute respiratory syndrome (SARS) coronavirus and environmental contamination in SARS outbreak units. J Infect Dis 2005; 191:1472–1477

3 Xiao WJ, Wang ML, Wei W, et al. Detection of SARS-CoV and RNA on aerosol samples from SARS-patients admitted to hospital. Zhonghua Liu Xing Bing Xue Za Zhi 2004; 25:882–885

4 Tran TH, Nguyen TL, Nguyen TD, et al. Avian influenza A (H5N1) in 10 patients in Vietnam. N Engl J Med 2004; 350:1179–1188

5 Ungchusak K, Auewarakul P, Dowell SF, et al. Probable person-to-person transmission of avian influenza A (H5N1). N Engl J Med 2005; 352:333–340

6 Goldmann DA. Transmission of viral respiratory infections in the home. Pediatr Infect Dis J 2000; 19:S97–S102

7 Goldmann DA. Epidemiology and prevention of pediatric viral respiratory infections in health-care institutions. Emerg Infect Dis 2001; 7:249–253

8 Yu IT, Wong TW, Chiu YL, et al. Temporal-spatial analysis of severe acute respiratory syndrome among hospital inpatients. Clin Infect Dis 2005; 40:1237–1243

9 Somogyi R, Vesely AE, Azami T, et al. Dispersal of respiratory droplets with open vs closed oxygen delivery masks: implications for the transmission of severe acute respiratory syndrome. Chest 2004; 125:1155–1157

10 Good ML. Patient simulation for training basic and advanced clinical skills. Med Educ 2003; 37(suppl):14–21

11 Meka VV, van Oostrom JH. Bellows-less lung system for the human patient simulator. Med Biol Eng Comput 2004; 42:413–418

12 So CY, Gomersall CD, Chui PT, et al. Performance of an oxygen delivery device for weaning potentially infectious critically ill patients. Anaesthesia 2004; 59:710–714

13 Goodwin JA, van Meurs WL, Sa Couto CD, et al. A model for educational simulation of infant cardiovascular physiology. Anesth Analg 2004; 99:1655–1664

14 Lampotang S, Lizdas DE, Gravenstein N, et al. An audible indication of exhalation increases delivered tidal volume during bag valve mask ventilation of a patient simulator. Anesth Analg 2006; 102:168–171

15 Anderson V. Comparisons of peak SAR levels in concentric sphere head models of children and adults for irradiation by a dipole at 900 MHz. Phys Med Biol 2003; 48:3263–3275

16 Hall SD. An investigation of the turbulent backward facing step flow with the addition of a charged particle phase and

electrostatic forces. PhD dissertation. University of New South Wales, Sydney, NSW, Australia, 2001

17 Soo SL. Fluid dynamics of multiphase systems. Toronto, ON, Canada: Blaisdell Publishing Company, 1967

18 Cole EC, Cook CE. Characterization of infectious aerosols in health care facilities: an aid to effective engineering controls and preventive strategies. Am J Infect Control 1998; 26:453–464

19 Crowe C, Sommerfeld M, Tsuji Y. Multiphase flows with droplets and particles. Boca Raton, FL: CRC Press, 1998

20 Seto WH, Tsang D, Yung RW, et al. Effectiveness of precautions against droplets and contact in prevention of nosocomial transmission of severe acute respiratory syndrome (SARS). Lancet 2003; 361:1519–1520

21 Lau JT, Fung KS, Wong TW, et al. SARS transmission among hospital workers in Hong Kong. Emerg Infect Dis 2004; 10:280–286

22 Fraser C, Riley S, Anderson RM, et al. Factors that make an infectious disease outbreak controllable. Proc Natl Acad Sci U S A 2004; 101:6146–6151