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Understanding droplets produced by nebulisers and respiratory activities

Key Messages

1. The size of large droplets produced during respiratory activities such as coughing can be larger than 50-100 μm . These droplets tend to evaporate quickly and contribute to both airborne and droplet transmission of disease.
2. Large droplets from respiratory activities can travel up to 1.5 m, which agrees well with the established range of infection due to droplet transmission. The distance between beds should be greater than 1.5 m.
3. Large droplets cannot be removed effectively from a room using currently available ventilation systems. Such droplets leave the air via surface deposition on floors, beds, and the patient's body, etc.
4. Taking nasopharyngeal aspirates can stimulate coughing and promote aerosol generation.
5. Nebulisers generate very fine droplets ($<1 \mu\text{m}$) and large volumes can escape through the holes in ventilator facemasks. These fine droplets may be contaminated by the patient's exhalation in the mask.

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Introduction

Of the various infection transmission routes, droplets and airborne routes are the most interesting in terms of ventilation and indoor air filtration. There have been a number of studies into the number and size of droplets of saliva and other secretions produced by respiratory activities¹⁻⁵ and excellent reviews have been published.^{6,7} The size of droplet nuclei produced by sneezing, coughing, and talking is likely to be a function of the generation process and the environmental conditions.^{1,2} The actual size distribution of droplets is also dependant on parameters such as the exhaled air velocity, the viscosity of the fluid, and the flow path (ie through the nose, the mouth, or both). There is also great individual variability.^{4,5}

Two crucial disease transmission issues are what constitutes 'large droplets' and how far such droplets can travel. Large droplet transmission occurs "when droplets containing microorganisms generated by the infected person are propelled a short distance through the air and deposited on the host's conjunctivae, nasal mucosa, or mouth".⁸ 'Short distances' have been defined as 1 to 1.5 m from the source person⁹ and large droplets were initially defined as droplets larger than 100 μm in diameter.¹⁰ Elsewhere in the literature, however, droplets larger than 5-10 μm are often treated as large droplets.⁸ The critical size of so-called large droplets is a function of many physical parameters such as the relative humidity, the ambient air velocity, and ambient air temperature. Knowledge of the critical size of large droplets is crucial for developing effective control methods such as ventilation and for determining filtration efficiency.

In his now classic study of airborne infectious disease transmission, Wells¹⁰ was the first to identify the difference between disease transmission via large droplets and airborne routes. Wells found that under normal air conditions, droplets smaller than 100 μm in diameter dried out before falling 2 m to the ground, that is, from human height. This finding established the theory that droplet and droplet nuclei disease transmission depends on the size of the infectious droplet.

Droplets play an important role in the transmission of some respiratory infections, yet there is a surprising lack of knowledge about respiratory droplets, particularly about the effect of evaporation and the distance of droplet spread. More accurate and detailed analysis and measurement of the processes involved in droplet evaporation and movement in indoor environments is needed.

Aims and objectives

The main objectives of this study were:

- (1) to study the number and size distributions of droplets produced during breathing, coughing, talking, the use of nebulisers, and taking of nasopharyngeal aspirates;
- (2) to determine the dispersion characteristics of droplets of different sizes in a room environment after being expelled; and
- (3) to determine the critical factors affecting the penetration of exhaled droplets from one person into the breathing zone of another. This information will provide new understanding of the mechanisms governing airborne and droplet

transmission of diseases as well as providing new ideas for the design of ventilation systems in hospital wards.

Methods

This study was conducted from December 2004 to November 2006.

Number and size distribution of droplets generated during respiratory activities

A small airtight box was constructed as done in previous studies.³ To collect large droplets, glass microscope slides and strips of water-sensitive paper (both 76 mm x 26 mm) were attached to the four walls of the box prior to each test, ie the back wall, left wall, right wall, and floor. Water-sensitive paper is a specially coated yellow paper that turns blue when exposed to water droplets, providing a rapid visual indication of droplet size and density. Small droplets or droplet nuclei suspended in the air were measured using a 16-channel dust monitor (Filter-check SubMicron Aerosol Spectrometer/Filter Efficiency Monitor, Model 1.108, Grimm Technologies Inc, GA, US), able to provide real-time size measurements of particles from 0.5 to 20 μm . Experiments involving nebulisers and nasopharyngeal aspirates were conducted at the Queen Mary Hospital, Hong Kong.

Droplet dispersion

The droplet dispersions of respiratory plumes produced by a mannequin were studied in the full-scale severe acute respiratory syndrome (SARS) ward test room at the University of Hong Kong. The number and size distribution of droplets/particles at different distances from the mannequin were measured. The same conditions were also studied using computational fluid dynamics simulations.

Penetration of breathing flows and nebuliser discharges

These were studied in the full-scale SARS ward test room at the University of Hong Kong and in a test room at the Aalborg University, Denmark. The respiratory flow patterns and droplet concentration (number per unit volume) profiles were determined. Air currents and the distance between the two persons (or beds) were studied under different environmental conditions, ie in a still, ambient environment, in a mixed air ventilated room, and in a ceiling supply and low-exhaust ventilated room.

Results

The average size of droplets produced by coughing and other respiratory activities can be larger than 50-100 μm , but they tend to evaporate quickly. Droplets generated by respiratory activities can be responsible for both airborne and droplet transmission of diseases. Taking nasopharyngeal aspirates (NPA) can stimulate coughing and promote the generation of aerosols.

Although measurement is technically quite difficult, we

were able to detect droplets generated from taking NPA; the number and size of these droplets were smaller than those due to respiratory activities. In contrast, nebulisers generated very fine droplets ($<1 \mu\text{m}$). Large volumes of these fine droplets can escape through the holes in the nebuliser facemask and may be contaminated by the patient's exhalations. As nebulisers do not generate large droplets, it is probably more likely that nebuliser use is associated with airborne transmission of disease.

The so-called large droplets seen in droplet transmission were larger than 50-100 μm in this study, which is different from current understanding. Large droplets produced by respiratory activities can travel a longer distance—about 1.5 m for breathing, which correlates with the range of infection caused by droplet transmission. Current ventilation systems cannot remove large droplets effectively from a room. These droplets form surface deposits on the floor, the bed, and the patient's body. The lowest level of exhaust in the current Centers for Disease Control and Prevention—recommended ventilation system appears to be unnecessary. The distance between beds should be greater than the distance travelled by the large droplets (1.5 m) but this distance does not affect the ventilation performance for the airborne transmission route.¹¹

Discussion

This study demonstrates the feasibility of measuring respiratory droplets produced during talking and coughing in a natural manner. The use of glass slides to detect droplet number, size, and density shows considerable promise, although scanning and analysing the droplet stain-marks are very time-consuming activities.

It was difficult to capture all the droplets produced during expiratory activities. If size distribution data are available, the total number of droplets produced may be estimated from the total mass measurement. There is only one report of a study measuring the total mass.¹²

The mask and plastic bag methods commonly used to capture respiratory droplets for study did not fit the face perfectly. Gaps between the face and the mask enabled droplets to escape during coughing. Droplet evaporation occurs during the process. Saliva on the lips may touch the mask or plastic bag. Condensation of water vapour in exhaled breath occurs in the plastic bag and droplets may be re-inhaled from the plastic bag. All these may influence the results.

We found that the total mass measured in experiments was much larger than that calculated from measurements of droplet number and size. When measuring droplet number and size, only a fraction of the droplets expelled were captured, reducing the calculated total mass. When measuring droplet total mass, residues other than respiratory droplets were collected, thus increasing the apparent total mass.

This study supports the belief that talking and coughing play important roles in respiratory droplet generation, and provides more information about respiratory droplets produced by healthy subjects. As expected, more small droplets were produced by the more violent activity of coughing.

In an earlier paper, we have presented the results of a detailed full-scale experimental study on the interactions of breathing flows between two patients lying in bed, and between a patient lying in bed and a standing health care worker in a ward with three different ventilation systems.¹¹ It was found that downward ventilation with an air change rate of 4 air changes per hour results in a mixing type of ventilation. The effectiveness of downward ventilation in different parts of the room is similar to the conventional mixing ventilation formats that are commonly used in general hospital wards.

In a mixing ventilation environment, our study showed that, over distances of 1.0, 0.6, and 0.3 m between beds, it had no significant impact on the personal exposure index of the patient exposed to the pollutant released from the source patient in a neighbouring bed.

Based on our data, both mixing and downward ventilation systems are recommended for hospital wards with multiple beds. Further study is needed to demonstrate the potentially superior particle removal performance by downward ventilation systems and identify whether 'dead' areas with incomplete mixing exist when using the downward ventilation system.

Our results demonstrated that the exhalation jet of a patient lying down and facing sideways can travel a very long distance, assisted by thermal stratification along the exhaled air direction in a ward ventilated by displacement. This raises the possibility of a high personal exposure level if the receiving individual—either a patient or a health care worker—is located in the exhalation jet. Displacement ventilation could remove the exhaled gaseous or fine particles effectively if the source patient is facing up. Moreover, a high concentration zone of exhaled droplet nuclei due to thermal stratification locking was also observed in displacement ventilation. Our results do not support the use of displacement ventilation in hospital wards.¹¹

Recommendations

1. There is some confusion in the infection control literature about droplet size during droplet transmission. The confusion may be caused by the differences between large droplets at the site of generation (ie when exhaled) and the residues left by large droplets in the room (ie after evaporation). At exhalation, large droplets may measure 50 to 100 μm while their residues may be much smaller.
2. The isolation room ventilation and airflow pattern affects both the airborne and droplet transmission of diseases. The current ventilation system used in hospital wards is not ideal.

3. The distance between hospital beds should be greater than the distance travelled by large droplets (1.5 m). Thus, bed distance should be determined by the mechanisms of droplet transmission, not airborne transmission.
4. Displacement ventilation should not be used in hospital wards and/or isolation rooms.
5. Nebulisers generate very fine droplets ($<1 \mu\text{m}$) and large volumes of these fine droplets can escape through the holes in the mask. The use of nebulisers is probably more likely to be associated with airborne transmission of disease.

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- (1) Qian H, Li Y, Nielsen PV, Hyldgaard CE, Wong TW, Chwang AT. Dispersion of exhaled droplet nuclei in a two-bed hospital ward with three different ventilation systems. *Indoor Air* 2006;16:111-28.
- (2) Xie X, Li Y, Chwang AT, Ho PL, Seto WH. How far droplets can move in indoor environments: revisiting Wells' evaporation-falling curve. *Indoor Air* 2007;17:211-25.
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