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The influence of human walking on the flow and airborne transmission in a six-bed isolation room: Tracer gas simulation

Jian Hang [a], Yuguo Li [b,*], Ruiqiu Jin [a]

[a] Department of Atmospheric Sciences, School of Environmental Science and Engineering, Sun Yat-Sen University, Guangzhou, PR China
[b] Department of Mechanical Engineering, The University of Hong Kong, Haking Wong Building, Pokfulam Road, Hong Kong Special Administrative Region

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ABSTRACT

By performing unsteady CFD simulations using RNG $k-\varepsilon$ model and dynamic mesh technique, this paper investigates how the walking motion of health care worker (HCW) influences gaseous dispersion in a six-bed isolation room with nine downward supplies and six ceiling-level or floor-level exhausts. The flow near and behind HCW is easily affected by HCW motion. The flow disturbance induced by HCW walking with swinging arms and legs is a mixing process. The walking HCW displaces air in front of it and carries air in the wake forwardly, meanwhile pressure difference drives air from two lateral sides into the wake. HCW motion (0–5.4 s) indeed induces a little gaseous dispersion, but the residual flow disturbance after HCW stops (5.4 s–25.4 s) induces more gaseous agent spread and it requires more than 30–60 s to approximately recover to the initial state after HCW stops.

Although HCW motion indeed affects airborne transmission, but its effect is less important than ventilation design. No matter with or without HCW motion, the ceiling-level exhausts perform much better in controlling airborne transmission than the floor-level exhausts with the same air change rate (12.9 ACH). Smaller air change rate of 6 ACH experiences higher concentration and more gaseous spread than 12.9 ACH. In contrast to the realistic human walking, the simplified motion of a rectangular block produces stronger flow disturbance. Finally surface heating of HCW produces a stronger thermal body plume and enhances turbulence near HCW, thus slightly strengthens airborne transmission.

1. Introduction

Airborne transmission is one of the main spread routes for a number of infectious diseases including smallpox, tuberculosis, severe acute respiratory syndrome (SARS) and influenza [1–5]. Specially there is an expected high risk of infection from patients to health care workers (HCWs) and other patients during an outbreak of such airborne diseases in hospitals [2–5]. The aim of mechanical ventilation systems with supplies and exhausts is to control air movements to protect HCWs and other patients from the polluted air by the infected patients. Effective mechanical ventilation design has been considered to be important for minimizing transmission of airborne diseases in hospital isolation rooms [2–5].

There have been a number of related full-scale experiments and computational fluid dynamic (CFD) simulations studying how different ventilation systems disperse and remove gaseous contaminants, exhaled particles and droplets from various indoor environments [1–20]. The displacement ventilation has been considered effective and widely used for indoor air quality control in general indoor environments [20], however in hospital isolation rooms, Qian et al. [14] and Yin et al. [19] found that the displacement ventilation may or may not provide a better performance of removing tracer gas and/or fine particles in the breathing zone depending on the location of the exhaust. Previous investigations on mixing ventilations in hospital isolation rooms [17,18] suggested that, if the upward thermal body plumes are considered in an isolation room with downward supply air streams, the ceiling-level exhausts are more efficient than the floor-level exhausts in reducing airborne transmissions. Some literature [3,21,22] provided good reviews.

In recent years, a few investigations have indicated that transient events such as human movements play an important role on indoor dynamic airflows and contaminant dispersion [23–34]. However full-scale experimental investigations of how human movements affect dynamic airflows and airborne transmission are difficult and high-quality experimental data with meaningful temporal and spatial resolution are rare so far [23–27]. The application of dynamic mesh technique combined with CFD simulations

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* Corresponding author. Tel.: +86 852 28592625; fax: +86 852 2858 5415.
E-mail addresses: hangj3@mail.sysu.edu.cn (J. Hang), liyg@hku.hk (Y. Li).

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provides a promising tool for such investigations [26–34]. Poussou et al. [27] and Mazumdar et al. [28] carried out small-scale experiments and CFD simulations to study the impact of human movement on airborne transmission in airliner cabins, finding that the human-induced wake may carry contaminant to positions far from the source location. Choi and Edward [29,30] performed large eddy simulations to explore how realistic human walking affects indoor airflows and contaminant transport between two rooms through a door way and the shared hall or vestibule. They first found that [29] the human wake may transport material over a distance of 8 m when there is no ventilation system. The walking speed and the initial proximity of human from the doorway may affect the human-induced room-to-room contaminant transport. Then they reported that [30], with ventilation systems, human-induced wake motion did enhance compartment-to-compartment contaminant transport.

Reported nosocomial SARS outbreaks in hospital wards worldwide have reminded us that it requires to create a safe and healthy environment in hospital wards, i.e. protect HCWs and uninfected patients from the risk of infection during an outbreak of airborne or droplet-borne diseases. In hospital isolation rooms, there are usually mechanical ventilation systems with air change rates of higher than 4–6 ACH, which are higher than general mechanically-ventilated indoor environments. Thus the effect of HCW motion on dynamic airflow and airborne transmission in hospital isolation rooms possibly differs from other kinds of rooms and requires more special concern. Previous studies usually used a sharp-edged rectangular block to model a moving HCW in an one-bed isolation room [31–33]. The use of rectangular blocks possibly over-predicts the dynamic flow disturbance induced by HCW motion, considering that a realistic walking HCW is a moving blunt object with human profile [35] and swinging legs, moreover there is leakage between torso and arms as well as between two legs [29,30]. Shih et al. [31] found that although the velocity and pressure fields in an one-bed isolation room are easily affected by a moving person, however the moving body does not obviously affect the removal of gaseous contaminants. Mazumdar et al. [32] verified that the wake of moving objects can carry gaseous contaminants inducing a swing in the contaminant concentration at the breathing levels for 10–90 s, but the risk level in the ward change little with and without the movements. Wang and Chow [33] numerically investigated the effect of human walking on dispersion and deposition of expiratory particles (0.5–20 μm) in an one-bed isolation room, finding that HCW motion significantly affects the particles dispersion and depositions. The faster HCW motion, the less suspended particles in the isolation room. The findings of Wang and Chow [33] differ from the other two [31,32]. The possible reason is that, in Wang and Chow [33], the boundary conditions at all wall surfaces (i.e. including moving object) for particles is ‘trap’ condition with ‘deposition effect’, and particles may deposit onto HCW surfaces as it moves backwards and forwards, however for gaseous contaminants there is no deposition [31,32]. In addition, some literature treated the patient as the only heat source [31,33], and some considered the heat flux from HCW surface [32]. Further investigations are still required to investigate the difference between these two situations. Finally, apart from human movement, the influence of other transient events in enclosed indoor environments has also been investigated, such as changing of sheets on a patient's bed [32], the motion of door opening and closing [4,29–31,36–38].

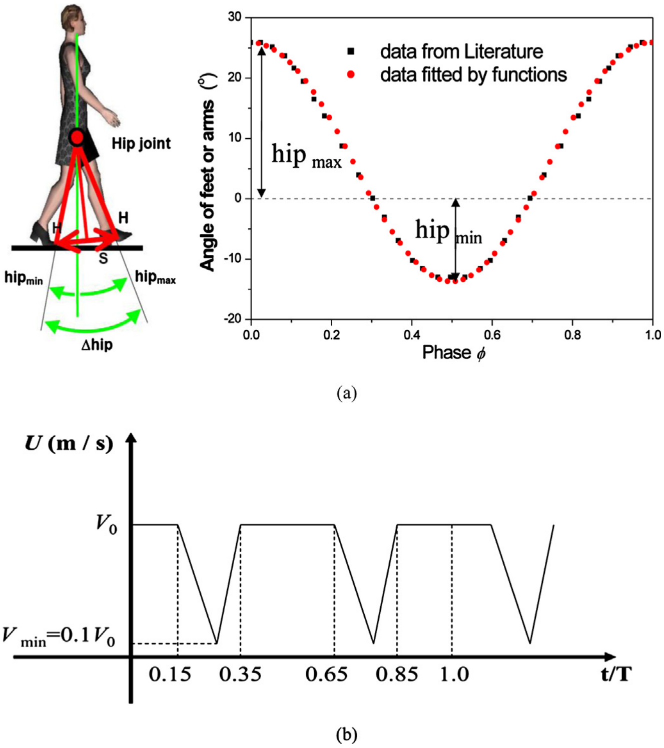
The purpose of this paper is to investigate how human walking influences the flow and airborne transmission in a six-bed hospital ward [18] which consists of different ventilation systems with nine downward supplies and either ceiling-level or floor-level exhausts. Respiratory material includes gaseous contaminants, exhaled particles and droplets. As a start, this paper only considers gaseous contaminants released from the source manikin's mouth. The following questions will be explored.

(1) What are the aerodynamic effects of a nearly realistic HCW walking and how it affects airborne transmission in a six-bed hospital isolation room?
(2) As verified by Qian and Li [18], the ceiling-level exhausts are confirmed more effectively in controlling airborne transmission than the floor-level exhausts. Is there the same conclusion when HCW walking occurs?
(3) For the ceiling-level exhausts with HCW walking, what changes for airborne transmission by lowering air change rate from 12.9 to 6 ACH?
(4) Is there difference when the realistic HCW walking is replaced by a simplified motion of a rectangular block? What difference occurs if the surface heat flux of HCW model is taken into account?

2. Methodologies

2.1. Modelling realistic human walking

Ronan et al. [39] studied the walking characteristics of human body. As shown in Fig. 1a (revised from the figure in Ronan et al. [39]), the swinging motion of both legs and arms is controlled by a temporal profile. If the normalized walking cycle events are mapped on the interval [0, 1] and the associated phase variable ϕ denotes the progression in the cycle, almost all the walking cycle events have a constant phase value whatever the walking velocity is [39]. Here $\phi = ft = t/T$ (f is the walking frequency, T is the cycle duration (s)). For the total hip flexion amplitude Δhip (see Fig. 1a), Ronan et al. [39] suggested a choice of $\mathrm{hip}_{\max} = -2\ \mathrm{hip}_{\min}$ which is



(a)

(b)

Fig. 1. Walking control and pattern according to Ronan et al. (2004): (a) Angle of feet and arms as human walking, (b) Moving velocity of human body (U, m/s).