Vertical Concentration Gradient of Influenza Viruses Resuspended from Floor Dust

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Keywords: walking, eddy diffusivity, influenza A virus, indoor

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Abstract

Resuspended floor dust constitutes up to sixty percent of the total particulate matter in indoor air. This fraction may also include virus-laden particles that settle on the floor after being emitted by an infected individual. This research focuses on predicting the concentration of influenza A viruses in resuspended dust, generated by people walking in a room, at various heights above the floor. Using a sonic anemometer, we measured the velocity field from floor to ceiling at 10-cm intervals to estimate the magnitude of turbulence generated by walking. The resulting eddy diffusion coefficients varied between 0.06 $m^2 s^{-1}$ and 0.20 $m^2 s^{-1}$ and were maximal at ~0.75-1 m above the floor, approximately the height of the swinging hand. We used these coefficients in an atmospheric transport model to predict virus concentrations as a function of the carrier particle size and height in the room. Results indicate that the concentration of resuspended viruses at 1 m above the floor is about seven times the concentration at 2 m. Thus, shorter people may be exposed to higher concentrations of pathogens in resuspended dust indoors. This study illuminates the possibility that particle resuspension could be a mode of disease transmission. It also emphasizes the importance of considering resuspension of particulate matter when designing ventilation systems and flooring in hospitals and residences.

Keywords: walking, eddy diffusivity, influenza A virus, indoor.

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Chapter 1. Introduction and Literature Review

It is well established that breathing suspended particulate matter could be very harmful for human health. Airborne particles, especially in the smallest size range of less than 10 micrometers, have very damaging health effects because of their ability to penetrate deep into the respiratory tract. The World Health Organization recently reported that air pollution is responsible for 7 million premature deaths per year worldwide and that the majority of these deaths, 3.3 million, are associated with indoor air pollution. The greatest risk is posed by particles. It has been observed that people especially in the industrialized nations are increasingly spending most of their time indoors. This has made it necessary for us to develop a fuller understanding of the behavior of particles in indoor air to be able to better assess the extent of our exposure to them.

Resuspended floor dust constitutes nearly sixty percent of the total particulate matter in indoor air (Alshitawi and Awbi, 2011; Ocak et al, 2012). This fraction may also include pathogen-laden particles that have settled on the floor after being emitted by an infected individual. The potential for exposure to pathogens resuspended from floor dust has been acknowledged in textbooks (Black, 2012; Mohanty and Leela, 2013) but, to our knowledge, has not been investigated quantitatively.

1.1 Particle resuspension

The presence of people in a room, and specifically their activity when walking across the floor, leads to elevated particle concentrations due to shedding and resuspension of floor dust. Thatcher and Layton (1994) measured the aerosol concentrations and particle size distributions in a two story residential setting in California. They collected the indoor particle samples through a 5 m long and 1 cm diameter copper tube which was placed at 2 m above the floor. The particle concentration inside the tube was determined through optical particle counting technique. The results indicated that walking activity in a room doubled the concentration of super micron particles in indoor air. They reported resuspension rate coefficients of the order of 10^{-5} to 10^{-4} h^{-1} while four people were moving around in a residence.

Freihaut and Bahnfleth (2007) studied the resuspension of allergen-containing particles due to human walking. They analyzed the complex floor disturbances generated during walking by resolving them into aerodynamic and mechanical components. The resolved forces were applied to a prepared particle bed in a controlled experimental chamber. The results indicated that aerodynamic forces dominated the mechanical forces in causing particle dispersion. A size resolved particle resuspension was measured by an optical particle counter. The counter measured the resuspension of particles ranging from 0.3 μm to >2 μm. They found that air swirl intensity generated by footsteps played a major role in resuspending the particles and reported resuspension rate coefficients ranging from 10^{-7} to 10^{-3} min^{-1}.

Qian and Ferro (2008) investigated particle resuspension due to human activities in a full scale experimental chamber. They studied the effects of flooring type, relative humidity, walking speed, the person's weight and ventilation patterns on concentration. Resuspension rate coefficients of the order of 10^{-4} to 10^{-2} h^{-1} were reported.

Several other recent studies have also shown that indoor particle concentrations are elevated by human activity. Alshitawi and Awbi (2011) measured the airborne particulate concentration in a classroom during different occupancy periods and found that students' presence greatly affected the airborne concentration. They focused primarily on three particle sizes: PM_1, $PM_{2.5}$ and PM_{10} where PM_1 stands for particulate matter measuring 1 µm or less, $PM_{2.5}$, particulate matter measuring 2.5 µm or less and PM_{10} is particulate matter measuring 10 µm or less. The particle concentrations were measured 1.20 m above the floor using two Grimm Portable Laser Aerosol Spectrometers. They concluded that the concentration of coarse particles, those larger than 2.5 µm, peaked when the students were walking across the hall. Ocak et al. (2012) measured the particle concentration inside a mosque and found that it peaked on crowded days particularly during prayers.

Hunt and Johnson (2012) used laser particle counters to investigate the aerosolization of dry soil in indoor air resulting from foot-stepping. They focused on the variability in resuspension of soil tracked in from the outdoors and found a direct correlation between resuspension and size of the dust reservoir on the floor and shoe sole.

Kai-Chung Cheng et al. (2010) studied the effect of foot traffic on indoor particle resuspension in a hospital environment. The experiments were carried out in a carpeted hallway. A Grimm dust monitor was used to measure particle resuspension at 0.3 m above the floor during walking. They determined that 87-90% variability in the indoor PM concentration was due to foot traffic. The coarse particles majorly contributed to the bulk of resuspended matter but they stayed in the air for lesser time than fine particles.

Jones and Nicas (2009) conducted experiments in a room scale experimental chamber to understand the fate of particles under natural and forced mixing. The transport of 3-µm and 14-µm particles was studied. Natural mixing occurred due to build up thermal convective currents in the chamber while two fans were used to generate forced mixing conditions. Results indicated that 3 µm particles settled uniformly across the chamber in natural as well as forced mixing conditions while 14 µm particles settled uniformly only during forced mixing.

1.2 Bioaerosols

Bioaerosols are airborne particulate matter that contains biological material, such as microorganisms, plant matter, insect parts, or human skin cells. Hospodsky et al. (2013) investigated the role of human occupancy in increasing the concentration of airborne bacteria. They found that during occupancy, resuspension from carpet and direct human shedding contributed significantly to elevate the respirable bacterial concentrations above the background level. As some bioaerosols contain disease-causing agents, the logical extension of these results is that occupants in a room inadvertently increase the risk of exposure to pathogenic bioaerosols while performing activities like walking.

Influenza is one of numerous infectious diseases that can spread via the airborne route. Whether transmission is dominated by aerosols or direct or indirect contact remains unknown, although our measurements of virus concentrations in indoor air suggest that airborne transmission is indeed feasible (Yang et al., 2011). Traditionally, it is divided into two modes: large droplet transmission involving close-range transport of droplets directly from the infected individual's respiratory system to the new host's nose or mouth, or aerosol transmission involving long-distance transport of droplet nuclei smaller than 5 μm in diameter resulting from the evaporation of large droplets (Brankston et al., 2007; Killingley and Nguyen-Van-Tam, 2013). We find the distinction between large droplets and droplet nuclei with a cutoff of 5 μm to be artificial and have instead proposed that the dynamics of virus-laden particles over a continuum of sizes control airborne transmission (Yang et al., 2011).

Given the ability of the influenza virus to survive outside the host for hours to days (Thomas et al., 2008; Yang et al., 2012), it seems quite likely that resuspension of viruses that have been deposited on the floor could serve as a route of influenza transmission.

1.3 Mathematical models

Observations of particle resuspension inspired development of mathematical models and numerical simulations of the phenomenon. Zhang and Ahmadi (2007) developed a rolling detachment model to assess particle detachment in the presence of capillary forces in turbulent flows. They found that capillary forces acting on the particles significantly increased the critical wind shear velocity required to detach the particles. Probing further into the dynamics of resuspended particles, Zhang et al. (2008) devised mathematical models for particle detachment, resuspension, and transport from a surface due to foot-stepping.

Can et al. (2012) simulated human walking in a model room to study particle resuspension. The Lagrangian method was used to simulate the particle resuspension. They concluded that particles larger than 5 μm are mostly responsible for increasing the airborne particulate matter concentration. Choi et al. (2012) performed a large eddy simulation (LES) of particle resuspension during foot-stepping. Their simulations revealed that particle resuspension primarily occurred during foot lift off as a result of formation of a particle cloud beneath the foot which is then transported by vortices formed near the edge of the foot. According to their findings, the resuspension rate coefficients increased with particle size in the 1-20 μm size range.

Most measurements of particle resuspension have been made at the height of the breathing zone, 1-1.5 m above the floor. The particle size distribution at different heights above the floor has not been investigated, to our knowledge. We hypothesize that the vertical dispersion of particles during human movement occurs due to the formation of eddies near the moving body. To predict the resulting particle transport, we must determine the magnitude of turbulence in the wake of a moving human body.

1.4 Measurement of indoor air turbulence

Several research groups have measured turbulence in indoor air, although none have described it in the vicinity of a person walking. Matthews et al. (1989) measured velocity profiles in different rooms of a household using an omnidirectional field anemometer. The measurements were made at ~0.9-1.4 m from the floor. They found a systematic variation in the air velocity between different rooms of the occupied house which depended on the type of activities going on in the rooms. Velocities ranging from 0 to 50 cm s^{-1} were recorded.

Heber et al. (1996) used a sonic anemometer to measure wind velocity profiles at forty locations inside a livestock building. The study argued that proper air distribution is necessary for the thermal comfort of animals and workers and that the turbulence intensity inside the building affects the dispersion of contaminants. An ultrasonic anemometer was used at 40 positions inside one half of the livestock building to determine the turbulence intensities at those positions. They found the turbulence to be isotropic at most locations inside the building except at solid boundaries, near the incoming air jet from the ceiling and heat sources such as animals. They also noted that turbulence time and length scales increased while energy dissipation and kinetic energy decreased with mean velocity and travel distance of the air jet in the building.

Tayler et al. (2004) of the National Institute of Occupational Safety and Health (NIOSH) used a three axis ultrasonic anemometer to measure airflow in a simulated underground mine environment. The results showed how the indoor geometry combined with inflow magnitude affects the airflow profiles. Upon widening the entry from 4 m to 5 m, the air flowed in a simpler

U shaped pattern as opposed to a twisted, 8-shaped pattern in the former case. Air flow velocity increased with increase in the intake quantity from 2.8 to 4.7 $m^3 s^{-1}$.

In a similar study, Wasiolek et al. (1999) conducted airflow studies in a simulated and an actual plutonium store room using a sonic anemometer. The air velocity measurements were made at 19 locations inside the simulated room at 0.6 m, 1.2 m and 1.8 m. The average velocities varied from 1.4 cm s^{-1} to 9.7 cm s^{-1}. In the actual room, the velocities were measured at breathing height (1.5 m) where values ranging from 9.9 to 35.5 cm s^{-1} were recorded.

Yost and Spear (1992) conducted tests using a sonic anemometer to measure indoor airflow patterns. The main focus of their study was on exploring the feasibility of using air velocity to describe dilution ventilation in a room. They measured the velocity fluctuations over a grid in a large test chamber which allowed them to capture small and large scale flow patterns inside the chamber. They found that the flow pattern inside the chamber was not homogenous from inlet to outlet despite a large air inlet. Velocities ranging from 3.6 cm s^{-1} to 28.5 cm s^{-1} were recorded.

1.5 Objectives

The main objective of this study is to predict the vertical concentration gradient of viruses that are resuspended from the floor during walking in a room, assuming that viruses have already deposited on the floor due to prior occupancy by an infected individual. We build a case study around the influenza virus, for which we have already modeled the airborne dynamics in terms of size distribution and infectivity (Yang and Marr, 2011). As part of this research, we measure turbulent wind velocity profiles induced by humans walking in a room; the novel data set fills a gap in the literature on this topic. The outcome of this work could be useful in understanding the epidemiology of influenza and designing more effective infection control mechanisms in hospitals and other facilities.

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Chapter 2. Vertical Concentration Gradient of Resuspended Dust: Are Shorter People Exposed to More Influenza Viruses?

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Abstract Resuspended floor dust constitutes up to sixty percent of the total particulate matter in indoor air. This fraction may also include virus-laden particles that settle on the floor after being emitted by an infected individual. This research focuses on predicting the concentration of influenza A viruses in resuspended dust, generated by people walking in a room, at various heights above the floor. Using a sonic anemometer, we measured the velocity field from floor to ceiling at 10-cm intervals to estimate the magnitude of turbulence generated by walking. The resulting eddy diffusion coefficients varied between 0.06 m^2 s^{-1} and 0.20 m^2 s^{-1} and were maximal at ~0.75-1 m above the floor, approximately the height of the swinging hand. We used these coefficients in an atmospheric transport model to predict virus concentrations as a function of the carrier particle size and height in the room. Results indicate that the concentration of resuspended viruses at 1 m above the floor is about 50% higher than the concentration at 2 m. Thus, shorter people may be exposed to higher concentrations of pathogens in resuspended dust indoors.

Keywords: walking, eddy diffusivity, influenza A virus, indoor.

Practical Implications

A person with influenza is likely to emit virus-laden particles into the air during coughing, sneezing, talking, or breathing, and some fraction of these will deposit on the floor. Forces generated by walking can resuspend the particles and create higher concentrations close to the floor and lower concentrations above it. Thus, shorter people may be exposed to higher concentrations of viruses that are resuspended from the floor. The same conclusion applies to resuspended floor dust in general, including toxic compounds, and other pathogens. This work could be used in support of epidemiological investigations into the incidence of influenza as a function of a person's height and to guide the design of more effective control strategies to reduce transmission of influenza.

Introduction

Resuspended floor dust constitutes up to sixty percent of the total particulate matter in indoor air (Alshitawi and Awbi, 2011; Ocak et al, 2012). This fraction may also include pathogen-laden particles that have settled on the floor after being emitted by an infected individual. In fact, resuspended dust has been shown to be enriched in bacteria relative to other sources of particles in indoor air (Hospodsky et al., 2013). The potential for exposure to pathogens resuspended from floor dust has been acknowledged (Black, 2012; Mohanty and Leela, 2013) but, to our knowledge, has not been investigated quantitatively.

The presence of people in a room, and specifically their movement, leads to elevated particle concentrations due to shedding and resuspension of floor dust. Thatcher and Layton (1994) found that walking activity in a room doubled the concentration of super micron particles in indoor air. They reported resuspension rate coefficients of the order of 10^{-5} to 10^{-4} h^{-1} while four people were moving around in a residence. Freihaut and Bahnfleth (2007) found that air swirls generated by footsteps played a major role in resuspending allergen-containing particles, with resuspension rate coefficients ranging from 10^{-6} to 10^{-2} h^{-1}. Qian and Ferro (2008) investigated the effects of flooring type, relative humidity, walking speed, the person's weight, and ventilation patterns on particle concentrations and reported resuspension rate coefficients of the order of 10^{-4} to 10^{-2} h^{-1}. Several other recent studies have also shown that indoor particle concentrations are elevated by human activity (Alshitawi and Awbi, 2011; Ocak et al., 2012; Hunt and Johnson, 2012). These observations have inspired the development of models of particle resuspension that account for the various forces involved when a foot or shoe contacts the ground (Zhang and Ahmadi, 2007; Zhang et al., 2008; Can et al., 2012; Choi et al., 2012).

Influenza is one of numerous infectious diseases that can spread via the airborne route. Whether transmission is dominated by aerosols or direct or indirect contact remains unknown, although our measurements of virus concentrations in indoor air suggest that airborne transmission is indeed feasible (Yang et al., 2011). Traditionally, it is divided into two modes: large droplet transmission involving close-range transport of droplets directly from the infected individual's respiratory system to the new host's nose or mouth, or aerosol transmission involving long-distance transport of droplet nuclei smaller than 5 μm in diameter resulting from the evaporation of large droplets (Brankston et al., 2007; Killingley and Nguyen-Van-Tam, 2013). We find the distinction between large droplets and droplet nuclei with a cutoff of 5 μm to be artificial and have proposed instead that airborne transmission is controlled by the dynamics of virus-laden particles over a continuum of sizes (Yang et al., 2011). Given the ability of the virus to survive outside the host for hours to days (Thomas et al., 2008; Yang et al., 2012), it seems quite likely that resuspension of viruses that have been deposited on the floor could be a route of influenza transmission.

Most measurements of particle resuspension have been made at the height of the breathing zone, 1-1.5 m above the floor. The particle size distribution at different heights above the floor has not been investigated, to our knowledge. We hypothesize that the turbulence generated by walking induces a vertical concentration gradient of particles. To predict transport of resuspended particles, we must determine the magnitude of turbulence in the wake of a moving human body. Several research groups have measured turbulence in indoor air (Matthews et al., 1989; Heber et al., 1996; Taylor et al. 2004; Wasiolek et al., 1999), but none have described it in the vicinity of a person walking.

The main objective of this study is to predict the vertical concentration gradient of viruses that are resuspended from the floor during walking in a room, assuming that viruses have already deposited on the floor due to prior occupancy by an infected individual. We build a case study around the influenza virus, for which we have already modeled the airborne dynamics in terms of size distribution and infectivity (Yang and Marr, 2011). As part of this research, we have measured turbulent velocity profiles induced by humans walking in a room; the resulting data set fills a gap in the literature on this topic. The outcome of this work could be useful in understanding the epidemiology of influenza and designing more effective infection control mechanisms in hospitals and other facilities.

Materials and Methods

Test environment

We measured velocity profiles induced by walking in a 4.20 m × 2.84 m × 2.35 m empty room, sealed to minimize infiltration, in Femoyer Hall on Virginia Tech's campus. The average indoor temperature was 26.3 °C. We used a 3D sonic anemometer (K probe, Applied Technologies Inc., Longmont, CO) to measure velocity fluctuations. The anemometer was located in the center of the room and was tagged with a bubble leveler to keep one axis perfectly vertical. A data acquisition program in LabView recorded velocity components u, v, and w at 10 Hz.

Measurement of eddy diffusion coefficients

We conducted three sets of experiments with 1, 2, or 3 persons walking in the room. They had an average height of 180 cm, which is the average height of males in the US. In each set of experiments, we positioned the anemometer at 10-cm increments starting from floor up to the ceiling and sampled for 4 min at each height. During the first 90 s, there was no walking. This interval was intended to capture the background turbulence. Walking began at 90 s and continued until 180 s. The first 30 s of walking was a transition period, and we used measurements between 120 s and 180 s to calculate eddy diffusion coefficients. The final 60 s of the sampling period was allotted to recording the decay in turbulence.

For the first set of experiments, 1 person walked at a speed of ~1.5 m s^{-1} in a circle of radius 0.75 m around the sonic anemometer. In the next two sets, 2 and 3 persons respectively walked in a predefined, non-circular pattern designed to avoid having a person follow in another's wake. Figure 1 shows the walking patterns for all three sets of experiments.

We calculated the eddy diffusion coefficient, k, at each height above the floor using the following equation:

$$k = \sigma_w \ L_l \tag{1}$$

where σ_w is the standard deviation of vertical velocity, w:

$$\sigma_w = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(w_i - \overline{w})^2} \tag{2}$$

and L_l is the turbulent mixing length. The turbulence under study is induced by shear flow and depends on the dimensions of the body generating it. Because the swing of the arm and leg during walking are chiefly responsible for creating turbulent eddies, we assumed a mixing length of 1 m, the approximate length of the limbs, in the succeeding calculations. We used a polynomial fit to the eddy diffusivities to parameterize them as a function of height for use in the particle transport model.

Particle transport model

Assuming that the flow is incompressible, the airborne particle concentration, *C*, satisfies the continuity equation (Seinfeld and Pandis, 2006) in the vertical direction:

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial z}(w - v_s)C = D\,\frac{\partial^2 C}{\partial z^2} + R(C) + S(z) \tag{3}$$

where *w* is the vertical advective velocity, *D* is the diffusion coefficient, *R(C)* is the rate of generation of the particles by chemical reaction, *S(z)* is the source term, and v_s is the gravitational settling velocity:

$$v_s = \frac{(\rho_p - \rho_f) g\, d^2}{18\mu} C_c \tag{4}$$

where ρ_p and ρ_f are particle density and air density, respectively, *d* is the diameter of the particle, μ is viscosity, and C_c is the Cunningham slip correction factor. We apply the drift-flux model (Chen et al., 2006) and assume that the advective velocity of the particles, *w*, is the same as that of the air. The vertical velocity and particle concentration can be decomposed into their mean, $\bar{w}$ and $\bar{C}$, and fluctuating components, w' and C', respectively. In our scenario, the term *R(C)* was zero because there was no chemical generation of particles. Also, turbulent dispersion was far stronger than diffusion (Brownian motion), and therefore we ignored the term $D\frac{\partial^2 C}{\partial z^2}$. With all the assumptions in place, the final form of the continuity equation is

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial z}[(\bar{w} + w' - v_s)(\bar{C} + C')] = S(t) \tag{5}$$

Time-averaging equation 5 generates the term $\overline{w'C'}$, which gives rise to the classic closure problem in physics. The problem is circumvented by calling upon K-theory:

$$\overline{w'C'} = -k\frac{dC}{dz} \tag{6}$$

where *k* is the eddy diffusion coefficient, which is a function of *z* in this research.

We finally arrive at the particle transport equation in the *z* direction with the overbars now removed:

$$\frac{\partial C}{\partial t} = k\ \frac{\partial^2 C}{\partial z^2} + \frac{\partial k}{\partial z}\ \frac{\partial C}{\partial z} - v_s\frac{\partial C}{\partial z} + S(z) \tag{7}$$

To discretize equation 7, we implemented a second-order accurate, Point Jacobi scheme and solved it using a FORTRAN program. Figure S1 in the online supporting information depicts the simulation grid with the *x*-axis as the iterating component and the *y*-axis as the spatial component, which spans 2.35 m, the height of the room, and is divided into 128 nodes. We used a time step of 9×10^{-4} s and sought the steady-state concentration representing the case in which walking is continuous. We iterated the equation until the solution converged, defined as occurring when a residual value of 10^{-9} was achieved at each node.

We implemented a second-order accurate, central differencing scheme in the core of the space, Zone 1 in Figure S1:

$$\frac{\partial^2 \mathrm{C}}{\partial \mathrm{z}^2} = \frac{1}{\Delta z^2}(\mathrm{C}^{\mathrm{n}}_{\mathrm{i+1}} - 2\mathrm{C}^{\mathrm{n}}_{\mathrm{i}} + \mathrm{C}^{\mathrm{n}}_{\mathrm{i-1}}) \tag{8}$$

At the floor and the ceiling, nodes i=1 and i=imax, respectively, in Zone 2 in Figure S1, we implemented one-sided forward and backward differencing, as shown in equations 9, 10, 11 and 12, respectively:

$$\frac{\partial C}{\partial z} = \frac{1}{2\Delta z}(-3C_i^n + 4C_{i+1}^n - C_{i+2}^n) \tag{9}$$

$$\frac{\partial C}{\partial z} = \frac{1}{2\Delta z}(3C_i^n - 4C_{i-1}^n + C_{i-2}^n) \tag{10}$$

$$\frac{\partial^2 C}{\partial \mathrm{z}^2} = \frac{1}{\Delta \mathrm{z}^2}(2C_i^n - 5C_{i+1}^n + 4C_{i+2}^n - C_{i+3}^n) \tag{11}$$

$$\frac{\partial^2 C}{\partial \mathrm{z}^2} = \frac{1}{\Delta \mathrm{z}^2}(2C_i^n - 5C_{i-1}^n + 4C_{i-2}^n - C_{i-3}^n) \tag{12}$$

Substituting these equations into equation 7 produces the final expression for calculating the particle number concentration at node i=1:

$$\mathrm{C}_1^{\mathrm{n+1}} = \mathrm{C}_1^{\mathrm{n}} + \frac{\Delta \mathrm{t}}{\Delta \mathrm{z}^2}[\frac{v_s.\Delta \mathrm{z}}{2}\ (4C_2^n - 3C_1^n - C_3^n) + k_1(2C_1^n - 5C_2^n + 4C_3^n - C_4^n) + \frac{1}{4}\ (4k_2 - 3k_1 - k_3)(4C_2^n - 3C_1^n - C_3^n) + S(z)(\Delta z)^2] \tag{13}$$

Similarly at node i=imax, the expression is

$$\mathrm{C}_{\mathrm{imax}}^{\mathrm{n+1}} = \mathrm{C}_{\mathrm{imax}}^{\mathrm{n}} + \frac{\Delta \mathrm{t}}{\Delta \mathrm{z}^2}[\frac{v_s.\Delta \mathrm{z}}{2}\ (3C_{imax}^n - 4C_{imax-1}^n + C_{imax-2}^n) + k_{imax}(2C_{imax}^n - 5C_{imax-1}^n + 4C_{imax-2}^n - C_{imax-3}^n) + \frac{1}{4}\ (3k_{imax} - 4k_{imax-1} + k_{imax-2})(3C_{imax}^n - 4C_{imax-1}^n + C_{imax-2}^n) + S(z)(\Delta z)^2] \tag{14}$$

In Zone 1, for nodes i= 2 to i=imax-1, the final expression is

$$\mathrm{C}_{\mathrm{i}}^{\mathrm{n+1}} = \mathrm{C}_{\mathrm{i}}^{\mathrm{n}} + \frac{\Delta \mathrm{t}}{\Delta \mathrm{x}^2}[v_s \Delta \mathrm{z}\ (C_i^n - C_{i-1}^n) + k_i(C_{i+1}^n - 2C_i^n + C_{i-1}^n) + (k_{i+1} - k_i)(C_{i+1}^n - C_i^n) + \mathrm{S(z)}\ \Delta z^2] \tag{15}$$

The source term, *S(z)*, applies to the first node, i=1, and is expressed as

$$S = r\ L(t) A \tag{16}$$

where r is the resuspension rate coefficient, which is dependent on particle size, $L(t)$ is the particle loading per unit floor area, and A is the floor area subject to resuspension (Qian and Ferro, 2008).

Case study

We ran the model for a scenario in which the floor was seeded with virus-laden particles resulting from a person coughing 10 times at time t=0 in an unventilated room. We considered three separate simulations with 1, 2, and 3 persons walking in the room starting at t=10 min or t=120 min, times we explored in our previous work on virus dynamics in indoor air (Yang and Marr, 2011). Because relative humidity (RH) affects virus inactivation and particle resuspension, we considered RHs of 15%, 35%, 55%, 75%, and 95%, spanning the values typically found indoors. The air inside the room was assumed to be well mixed before walking began, at which point all remaining suspended viruses that had not yet settled were cleared from the air. This assumption allowed us to focus on resuspension and not to have to consider viruses that were still settling after being emitted from the original source. We assumed that the settled particles were uniformly distributed across the floor. A different set of assumptions could also be justified, but because we are more interested in the vertical concentration gradient than the absolute concentrations, our results can be generalized to many other scenarios.

We established the virus loading on the floor based on results of a model of virus removal from indoor air by gravitational settling and inactivation (Yang and Marr, 2011). The size distribution of droplets produced by coughing was lognormal with a geometric mean of 12.9 µm and a geometric standard deviation of 2.3, and the initial virus concentration in the droplets was 6.3×10^{-3} cm^{-3}. The droplets evaporated almost instantaneously to equilibrate with ambient RH, and droplets that were initially 100 μm in diameter shrank to 40-μm and 50-μm particles at RHs of 15% and 95%, respectively. We did not consider droplets of initial size larger than 100 μm. The concentration of suspended particles decreased exponentially over time due to gravitational settling, and the fraction of particles that settled to the floor was

$$f = 1 - \exp[\left(v_s \frac{A}{V}\right) t] \tag{17}$$

where *V* is the volume of the room. Using *f*, we calculated the particle loading, L, per unit area of the floor. We reduced the concentration of infectious viruses over the first 10 min or 120 min by a factor of $\exp(-k_d t)$ to account for inactivation over time, where k_d is a function of relative humidity (RH):

$$k_d = 0.0438\,RH - 0.00629 \tag{18}$$

We used resuspension rate coefficients that were experimentally determined by walking on a hard floor seeded with particles in a well-mixed chamber (Qian and Ferro, 2008). The researchers measured resuspension rate coefficients for particles up to a maximum size of 10 μm, and we linearly extrapolated these up to 50 μm on the basis of results of large eddy simulation modeling of particle resuspension (Choi et al., 2012). We plotted resuspension rate coefficients versus particle size presented in Table 3 of Choi et al. (2012) and found them to be linearly increasing in the large-particle regime. Figure 2 shows the resulting resuspension rate coefficients as a function of particle size, where the four data points are from experimental measurements (Qian and Ferro, 2008).

Qian and Ferro's (2008) measurements took place at 30% RH, and resuspension rate coefficients have been shown to depend on RH (Qian et al., 2014). Thus, we adjusted the rate coefficients to apply them over a range of RHs. The adjustment factor was based on a dimensionless number, η, the ratio of the force applied to resuspend particles to that applied to keep the particles on the ground. The force applied to resuspend particles is independent of the indoor environmental conditions. However, the force applied to keep the particles sticking to the floor varies with RH because of the formation of a water layer that increases surface tension between the particles and the ground. An empirical formula relates the adhesion force with RH (Hinds, 1999):

$$F_{adh} = 15\, d_p(0.5 + 0.0045(\%\mathrm{RH})) \tag{19}$$

where d_p is the particle diameter in micrometers and F_{adh} is in Newtons. The force of adhesion changes with RH, which in turn changes η. We assumed that η is directly proportional to the resuspension rate coefficient, so that it alters the experimentally determined value at 30% by the same fraction. By applying η, we determined the resuspension rate coefficients for all particle sizes at the five RHs of interest.

The initial condition was $C(z) = 0$ for our scenario. We set the eddy diffusion coefficient, k, to zero at node i=1 near the floor and at node i=imax near the ceiling because they are solid surfaces. Above head height, we observed that turbulence decreased to its background value, corroborating the assumption of zero turbulence at the ceiling.

Results

Turbulence profiles

Figure 3 shows time series of vertical velocity at varying heights resulting from one person walking around the sonic anemometer. The person began walking at 90 s and stopped at 180 s, so velocity fluctuations before and after this period were due to background turbulence in the room, including decay after the person stopped walking. At 90 s, the magnitude of velocity perturbations rose sharply and stabilized between 120 s and 180 s. We used the velocity perturbations in this 60-s window to calculate the eddy diffusion coefficients. At each height, the mean velocity was close to zero. It was negative, directed toward the floor, with 1 person but randomly varied in both directions during experiments with 2 and 3 persons.

The velocity fluctuations were largest 95 cm to 175 cm above the floor and lowest close to the floor as well as the ceiling. The autocovariance of vertical wind velocity, shown in Figure S2, illustrates this point further. While the turbulent flow field was highly correlated at 1 m from the floor for 1 person walking, the covariance was much lower at 2 m, which is above the head. The trend, however, was not consistent with more people. The zone of least covariance occurred at foot level in the experiment with 2 persons (Figure S2). The autocovariances were strong with 3 persons. It appears that 1 person constantly disturbed the flow field near the ground while walking in circles around the anemometer. However, when 2 persons walked in pattern shown in Figure 1, the turbulence quickly decayed near the floor before the other person could disturb the flow field. The difference in walking patterns may explain why the zone of least covariance occurred near the foot level in the experiment with 2 persons. The frequency of walking past the anemometer was higher with 3 persons, leading to stronger velocity autocovariances.

The resulting eddy diffusion coefficients are shown in Figure 4. Equations for a cubic polynomial fit to the data are also shown. The eddy diffusion coefficients increased, but not linearly, with the number of people walking in the room. The maximum diffusivities across the vertical span were 0.15 $m^2 s^{-1}$ with 1 person, 0.17 $m^2 s^{-1}$ with 2 persons, and 0.21 $m^2 s^{-1}$ with 3 persons. Because the walking pattern differed in each case, we did not necessarily expect the diffusivities to increase with the number of persons. The maximum values occurred at a height of ~0.75 m above the floor, the height of the swinging hand. Results for 1 person walking indicated that body movement affected air in a region nearly bounded by the human height. Turbulence dampened out rapidly above the human head, and only traces of turbulence were recorded 40 cm above the head. When more people were walking, the diffusivities above 1 m did not decrease as much with height, indicating the presence of a turbulent flow field above head height.

Viruses in floor dust

Figure 5 shows the size distribution of the number of infectious viruses on the floor as a function of RH at 10 min and 120 min. The diameter refers to that of the carrier particle, which depends on the size distribution of droplets emitted from a cough after they have evaporated to equilibrate with ambient humidity. Loading was much lower after 120 min because of inactivation of the viruses over time. At 15% RH, the inactivation rate was low, and over time, viruses associated with smaller particles accumulated on the floor, resulting in an apparent leftward shift of the distribution between 10 min and 120 min. Figure S3 shows the loading of carrier particles rather than viruses and emphasizes the accumulation of particles on the floor over time. At higher RHs, higher inactivation rates dominated, and concentrations of infectious viruses on the floor decreased with time, falling to near zero at the two highest RHs. Two competing processes, gravitational settling and inactivation, affected virus loading on the floor. Over time, the number of infectious viruses on the floor increased due to gravitational settling but decreased due to inactivation. Thus at low RHs, virus loading actually increased over time at smaller particle sizes as they continued to settle out from the air. Viruses associated with larger particles settled within the first 10 min and did not continue to accumulate on the floor, as they had already been removed from the air.

Virus resuspension

In determining the fraction of settled particles that were resuspended, we assumed that their size did not change while they were on the floor, though in fact they could agglomerate with other particles or gain mass from or lose it to the floor. Figures 6 and 7 compare the resuspension flux for each particle size at five RHs in terms of the number of particles resuspended per second and the number of infectious viruses resuspended per second, respectively, over an area of 1 m^2 by 1 person walking. The resuspension flux of infectious viruses was the product of the resuspension flux of particles and the number of viruses per particle, all specific to the particle size of interest. The curves end at different diameters for each RH because this is the largest size that remains after equilibration of a droplet that was initially 100 µm.

For viruses (Figure 7), resuspension flux was greater at lower RH across the entire size spectrum. Low RH favored higher virus loading on the floor and enhanced virus resuspension because of the lower adhesion forces under these conditions. The difference in the resuspension flux between 15% RH and 95% RH was a factor of ~4 after 10 min and ~150 after 120 min. Because these fluxes were extremely small compared to the total number of viruses on the floor, we may assume that the amount of viruses on the floor (i.e., the source) did not change significantly as particles were resuspended, or as they resettled to the floor.

Vertical concentration gradient of infectious viruses

The major objective of this study was to estimate the difference in exposure of people of different heights to resuspended viral particles in an indoor environment. Figure 8 shows the normalized vertical concentration gradient of infectious viruses that are resuspended by a single person walking at 15% and 95% RH, for different particle sizes. The x-axis is normalized to the virus concentration in the layer nearest to the ground for each particle size. At 15% RH, the largest particle size that remained after accounting for evaporation was 39.2 μm, so there is no curve for 50-μm particles in Figure 8a. The virus concentration profile was determined by multiplying the particle concentration at each height by the number of infectious viruses per particle. Because the larger particles carried more viruses (proportional to diameter cubed), even though their source strength was lower (Figure 6), they injected more viruses into the air (Figure 7). The normalized curves were independent of time but the number of viruses in the air would increase over time as more are resuspended from the floor by continuous walking, although continued inactivation would reduce the number of infectious viruses. The virus number distribution followed a hyperbolic shape that was more extreme for particles larger than 20 μm because of their larger settling velocities. Particles smaller than 10 μm varied more linearly over height. In the scenario with one person walking at 15% RH, the concentration at ceiling height was ~85% of that at the floor for 1-μm particles, but for the 40-μm particles, this fraction was 50%.

Compared to the case with 1 person walking, 2 persons resulted in higher fractions while 3 persons resulted in highest fractions, as shown in Figure 9, which totals the viruses over all particle sizes. At 15% RH, the loadings at node 1 with 1, 2, and 3 persons walking were 3.0 virus m^{-3}, 7.0 virus m^{-3}, and 10.0 virus m^{-3}, respectively. At 95% RH, these loadings were 7.61×10^{-1} virus m^{-3}, 2.0 virus m^{-3}, and 3.0 virus m^{-3}, respectively. The change in the distribution curves with addition of people to the room was the result of an altered turbulent flow field. At foot level, the eddy diffusion coefficients were highest, 0.1 $m^2\ s^{-1}$, with 3 persons walking and almost equal, 0.07 $m^2\ s^{-1}$ and 0.06 $m^2\ s^{-1}$, respectively with 1 and 2 persons. Hence, more resuspended particles were transported to higher levels with 3 persons compared to 1 or 2. With 2 persons, eddy diffusivities were larger over the vertical span than with 1 person. This causes the viruses to disperse more, increasing their fractions over the vertical span as shown in Figure 9.

At any particular instant, a child less than 1 m tall would be exposed to a concentration of resuspended viruses that is up to ~50% higher than that experienced by a 2-m tall adult. A 1.5-m tall person would be exposed to a concentration ~20% higher compared to a 2-m tall person. Apart from height, time and RH also affect the resuspended viral particle concentration. If two persons of the same height were exposed at 15% and 95% RH respectively, the one at 15% RH would be exposed to ~4 times the viral concentration that a person at 95% RH would after 10 min of walking. The difference in viral concentrations at the two RHs reaches a factor of ~150 after 120 min.

Discussion

Air flow induced by walking

Turbulent dispersion is the major physical process that disperses particles in the vertical direction during walking. Particles are simultaneously subject to gravity, which causes them to settle. The duet of these two processes governs the virus concentration at any given height above the floor when there is no advective transport. However, a walking person does generate non-zero vertical advective flow, particularly at ~0.75-1.25 m above the floor where the hand swings. In the interest of isolating the effects of particle resuspension, we have constructed and modeled a scenario that seems internally inconsistent (i.e., no advection, yet particles are resuspended by walking, which causes advection). It is possible that with enough people walking randomly around a room, the time-averaged mean velocity would be zero. Ventilation, which has not been considered in this study, would introduce advective flow in a room and would affect particle transport. For future studies, we recommend simulations using computational fluid dynamics to model particle resuspension under more realistic conditions.

The eddy diffusion coefficients reported here are a novel contribution to the literature and will enable improved understanding of the transport of resuspended particles indoors. The occurrence of the maximum eddy diffusivities at 0.75-1 m above the floor is probably due to the swinging motion of the hand, which causes rapid mixing at that height. By a similar argument, one might expect large fluctuations at foot level, too, but the ground dampens them. A completely different pattern of walking had to be designed when more people were added to the experimental study. The room in which the experiments were carried out was small, and therefore it was not possible for two people to walk in a circular path around the anemometer without following in each other’s turbulent wake. The addition of more people walking in a room generates less of an increase in eddy diffusivities than expected. With additional people, the eddy diffusivities are higher at and above head level due to the presence of a taller turbulent regime. Therefore, while adding more people does not cause a linear increase the magnitude of eddy diffusivities, it causes the zone of turbulence generated to extend further in the upward direction. A taller turbulent zone would promote more dispersion of particles over height.

Particle resuspension and the impact of indoor relative humidity

Previous studies have shown that the influenza virus survives best in droplets and aerosols at low RH (Yang and Marr, 2012). Particle resuspension is also favored at low RH because the capillary forces acting on the particles and adhering them to the floor are virtually non-existent in dry conditions (Zhang and Ahmadi, 2007). Furthermore, low RH results in greater evaporation of respiratory droplets and thus smaller particles, which remain suspended longer. Thus, low RH favors higher concentrations of resuspended influenza viruses and may be more conducive for virus transmission via particle resuspension for multiple reasons. This observation may help explain the seasonality of influenza in temperate regions, when wintertime heating reduces indoor RH to low levels (Engvall et al., 2005; Yang et al., 2011).

Other types of particles

Floor dust could act as a source of particles of any composition, not just influenza viruses, including toxic compounds such as polycyclic aromatic hydrocarbons (PAHs), endocrine disruptors, and others of concern. The mathematical model presented in this work is entirely physical and depends only on the particle's size, density, and characteristics of the turbulent flow field. Therefore it could be applied to study the vertical dispersion of any type of particle whose resuspension resulted from the walking activity. Our model applied an inactivation rate, which could be eliminated for the study of a conserved type of particle, or adjusted accordingly for one subject to decay.

Model sensitivity to resuspension rate coefficients

Qian et al. (2014) compiles resuspension rate coefficients and shows that they can vary over orders of magnitude from one study to the next, although the relationship with particle size is similar. Our work uses resuspension rate coefficients that were experimentally determined from measurements ~1.5 m above the ground in a well-mixed room for a 75-kg person walking at 114 steps per minute on a hard floor in a 30% RH environment (Qian and Ferro, 2008). There is some incongruity in applying these values to the ground-level node in our model because of the difference in height and assumptions about mixing. Using different values of the resuspension rate coefficient in our model would produce different absolute concentrations of viruses, but the vertical concentration profiles would retain the same shape. To address this uncertainty in more detail, we recommend that future experimental studies measure concentrations of resuspended particles at multiple heights above the floor.

Conclusions

Our findings indicate that turbulence generated in the wake of a moving human body is non-uniformly distributed across the vertical span of the room. Hand swing creates a highly turbulent zone at 0.75-1 m above the floor. Much less turbulence is observed near the foot due to dampening at the floor. The effect of turbulence is reduced above the head of the walker, but the reduction is more pronounced with 1 person walking than with more people.

There is likely to be a difference in the level of exposure of people of different heights to resuspended particulate matter indoors. Provided that mean vertical advective particle transport is minimal and resuspension from the floor is the major source of airborne particles, shorter people would be exposed to higher levels of resuspended particulate matter than would taller ones. Children who are less than 1 m tall could be exposed to ~50% higher concentrations of viruses compared to a person who is 2 m tall. Children are at the highest risk of exposure, plus they have weaker immune systems than do adults. And everyone may be at higher risk of exposure to resuspended particles when seated or lying down.

The results of this study call for further investigation into exposure to particulate matter indoors as a function of height. Both experimental measurements and epidemiological studies could verify whether increased exposure of shorter people to resuspended particles is a real phenomenon. This study illuminates the possibility that particle resuspension could be a mode of disease transmission. It also emphasizes the importance of considering resuspension of particulate matter when designing ventilation systems and flooring in hospitals and residences.

Acknowledgments

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Supplemental Information

Fig. S1. The numerical grid space used for simulation of concentrations. The grid is divided into 128 nodes in the vertical direction and traverses through iterations along the horizontal direction until the concentration at each node reaches its steady-state value.

Fig. S2. Vertical velocity autocovariances at three heights for (a) 1 person walking, (b) 2 persons walking, and (c) 3 persons walking.

Fig. S3. Number of particles in the floor dust per unit area at (a) 15% RH, (b) 35% RH, (c) 55% RH, (d) 75% RH, and (e) 95% RH.

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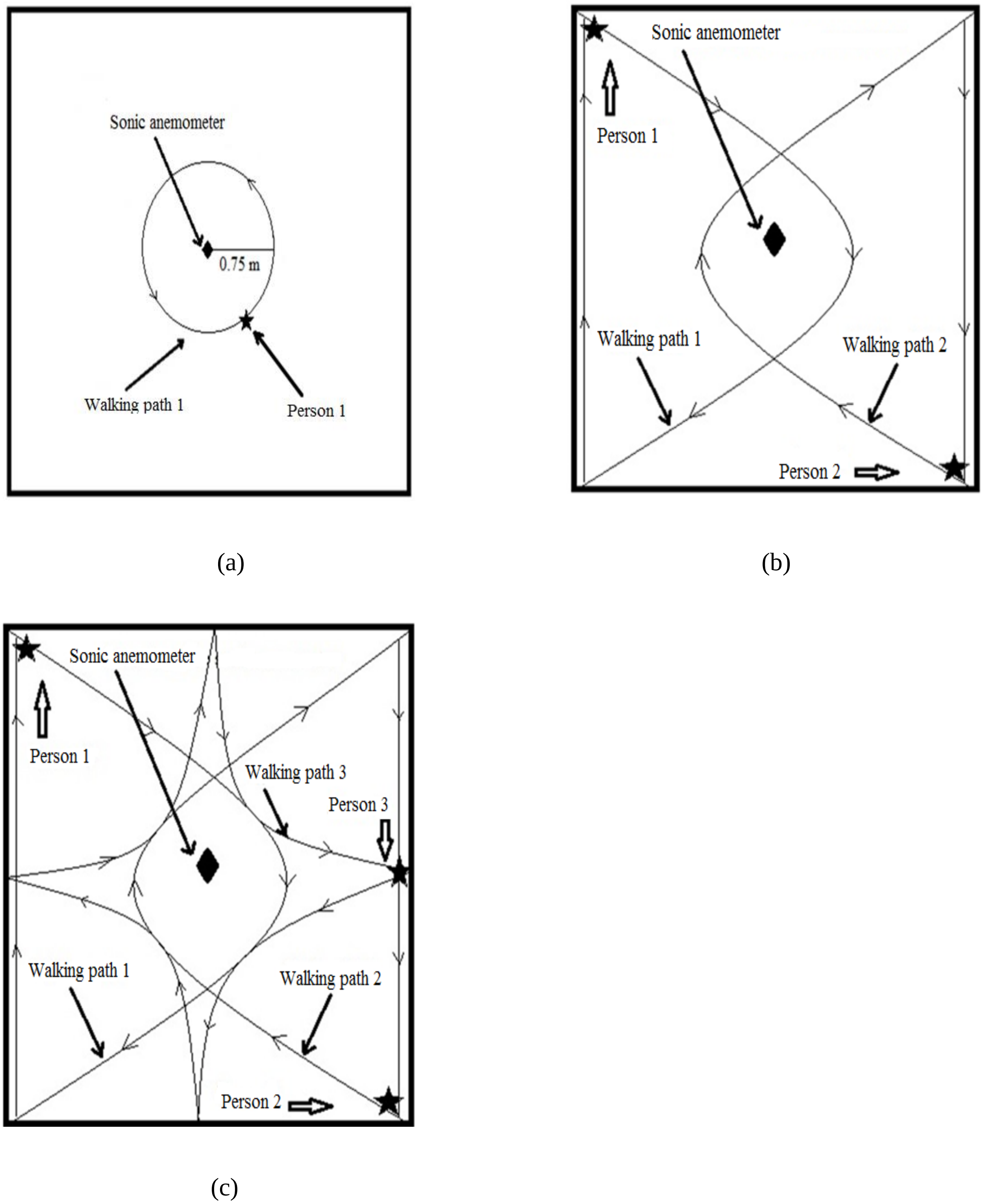


Figure 1. Walking patterns during measurement of velocity profiles with a sonic anemometer in the center of the room. (a) 1 person, (b) 2 persons, and (c) 3 persons.

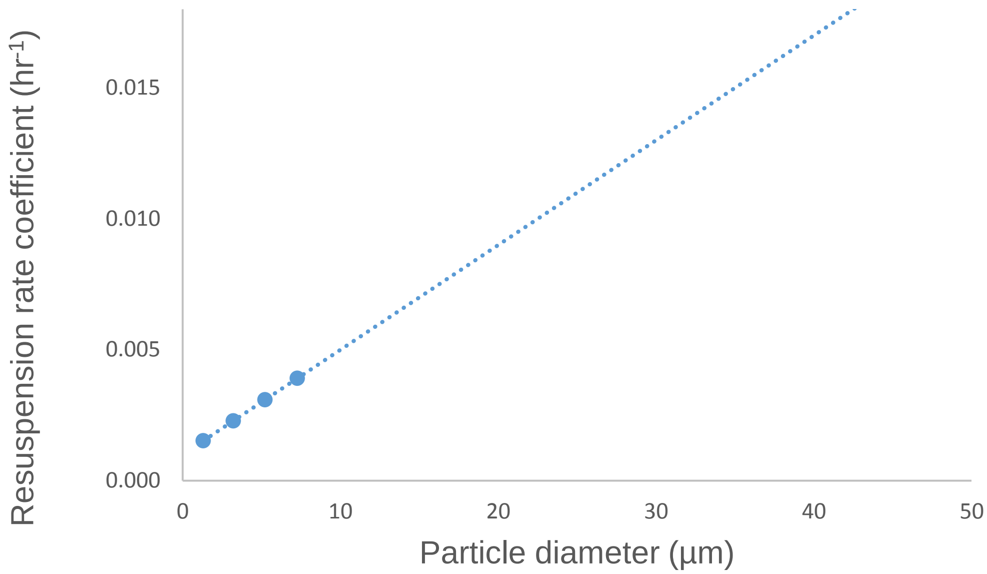


Figure 2. Particle resuspension rate coefficient as a function of particle size, extrapolated from four measurements by Qian and Ferro (2008). The values correspond to a 75-kg person walking at 114 steps per minute on hard flooring.

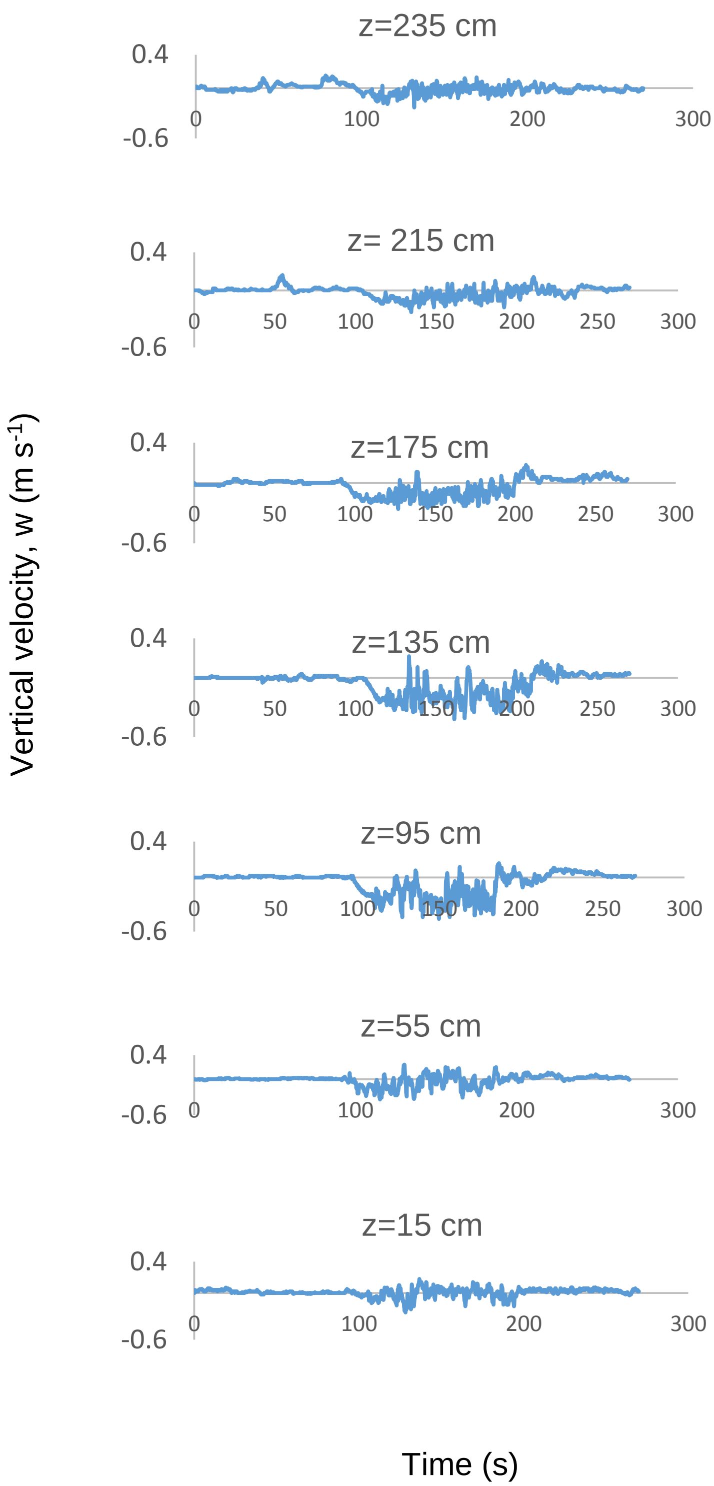


Figure 3. Time series of vertical velocity measured at the center of a circle walked around by 1 person, shown at varying heights above the floor. Walking commenced at 90 s and stopped at 180 s.

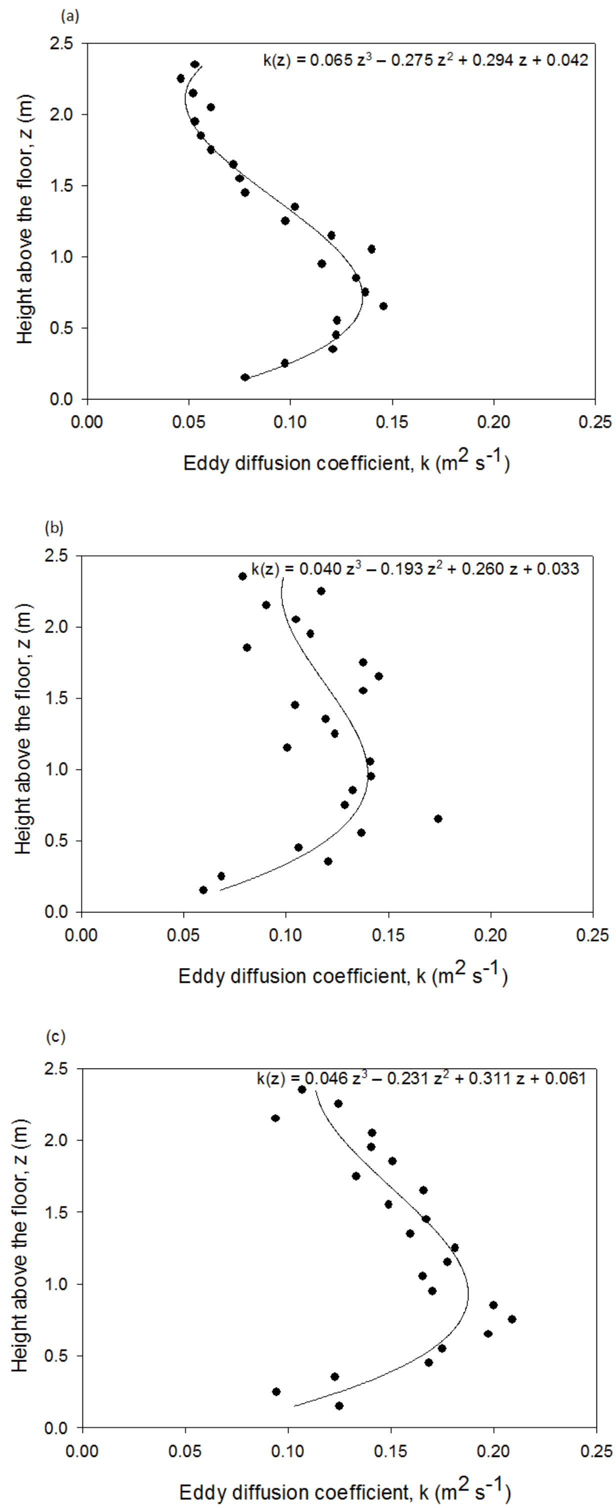
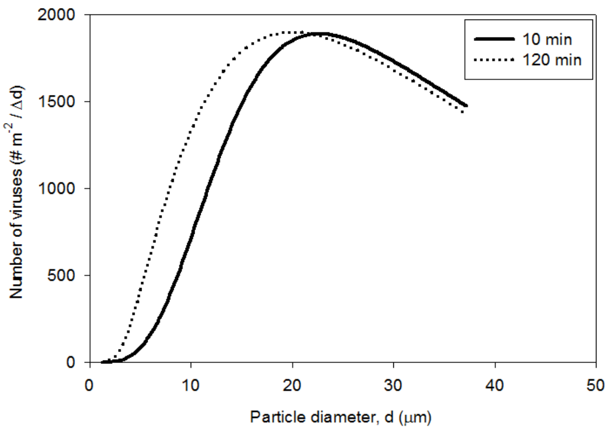


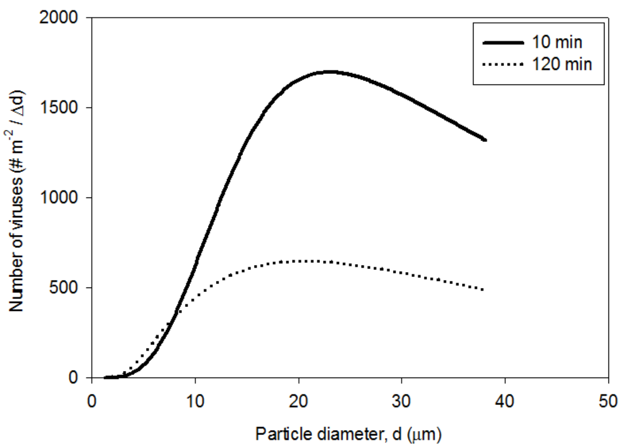
Figure 4. Turbulent eddy diffusivity profiles across the vertical span of the room for (a) 1 person, (b) 2 persons, and (c) 3 persons walking in the patterns shown in Figure 1.

(a)



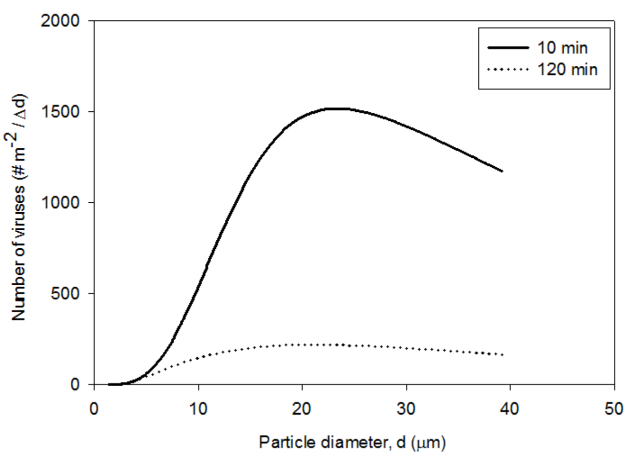
10 min
120 min
Number of viruses (# m-2 / Δd)
Particle diameter, d (μm)
2000
1500
1000
500
0
0
10
20
30
40
50

(b)

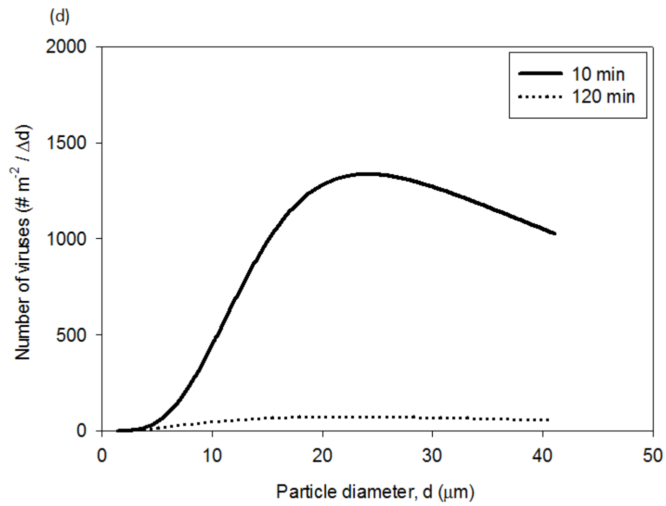


10 min
120 min
Number of viruses (# m-2 / Δd)
Particle diameter, d (μm)
2000
1500
1000
500
0
0
10
20
30
40
50

(c)



10 min
120 min
Number of viruses (# m-2 / Δd)
Particle diameter, d (μm)
2000
1500
1000
500
0
0
10
20
30
40
50



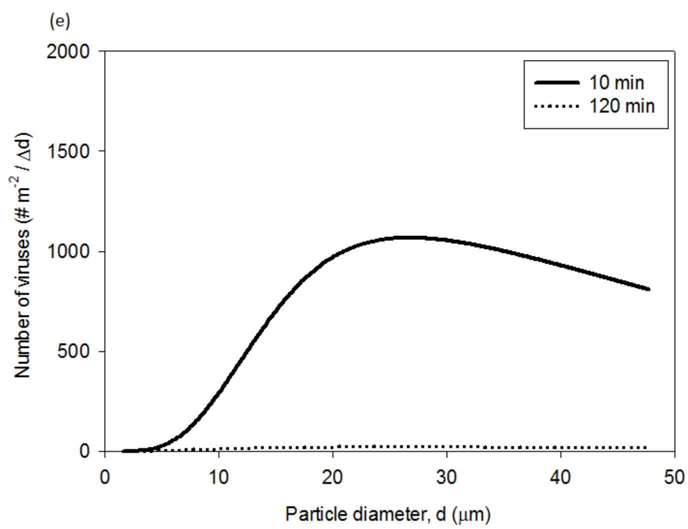


Figure 5. Number of viruses in the floor dust per unit area at (a) 15% RH, (b) 35% RH, (c) 55% RH, (d)75% RH, and (e) 95% RH.

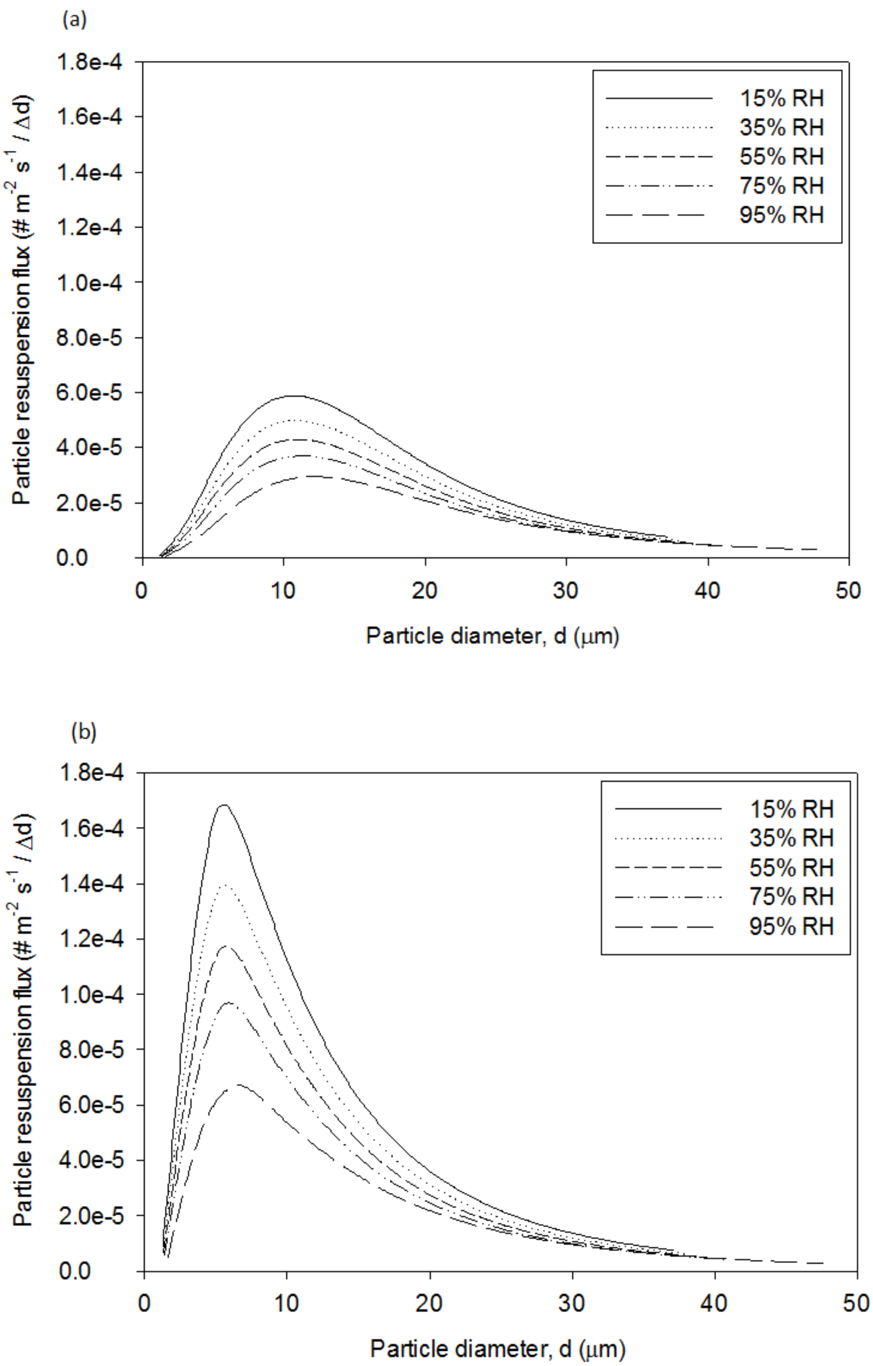


Figure 6. Resuspension flux of particles at ground level by 1 person walking (a) 10 min and (b) 120 min after coughing.

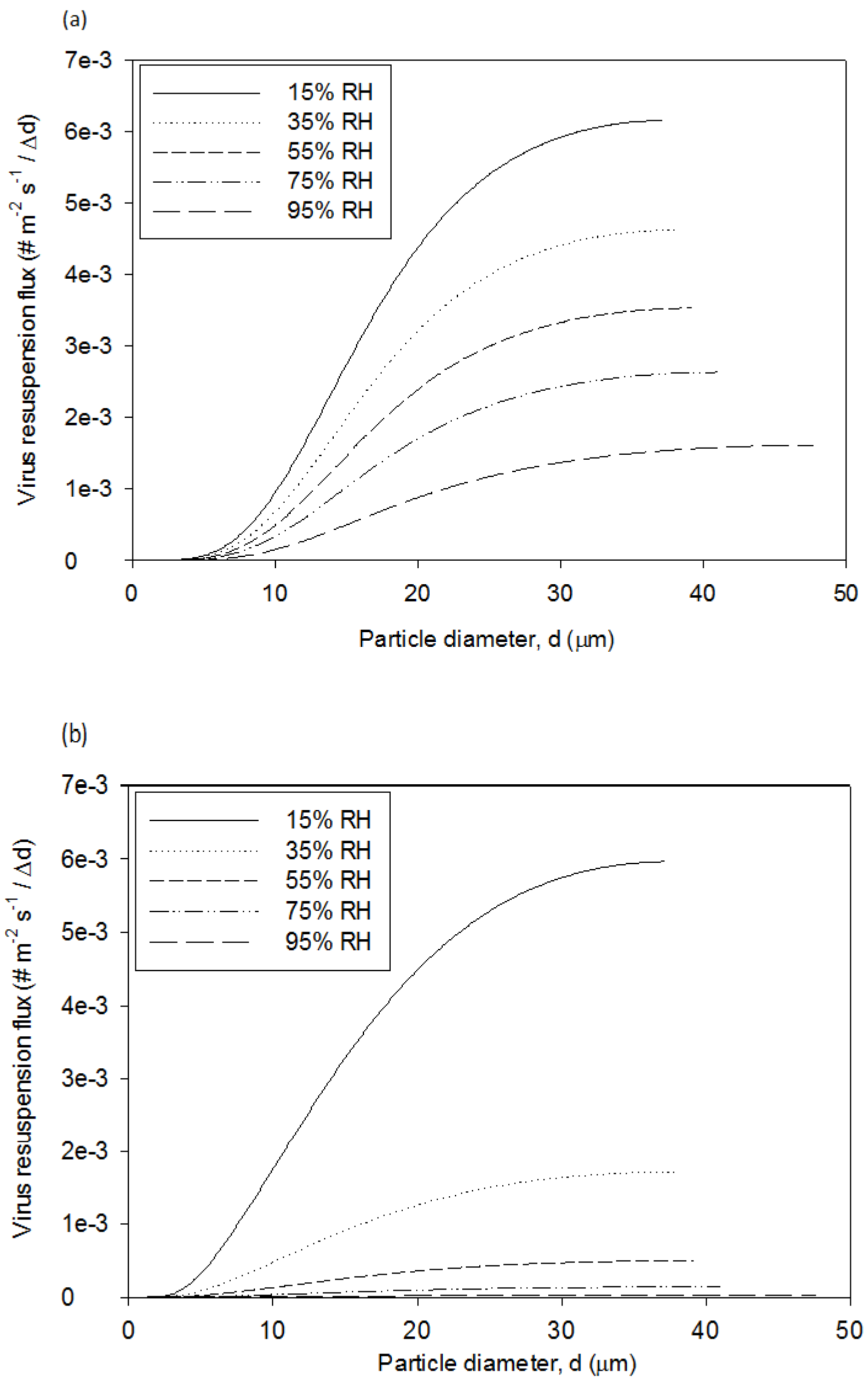
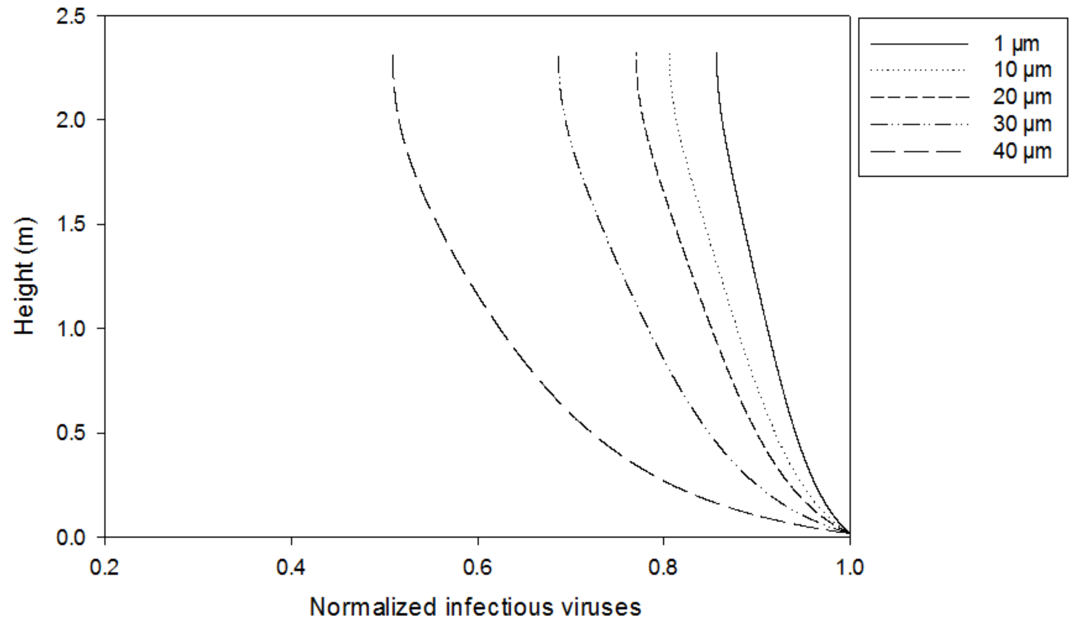


Figure 7. Resuspension flux of infectious viruses at ground level by 1 person walking (a) 10 min and (b) 120 min after coughing.

(a)



(b)

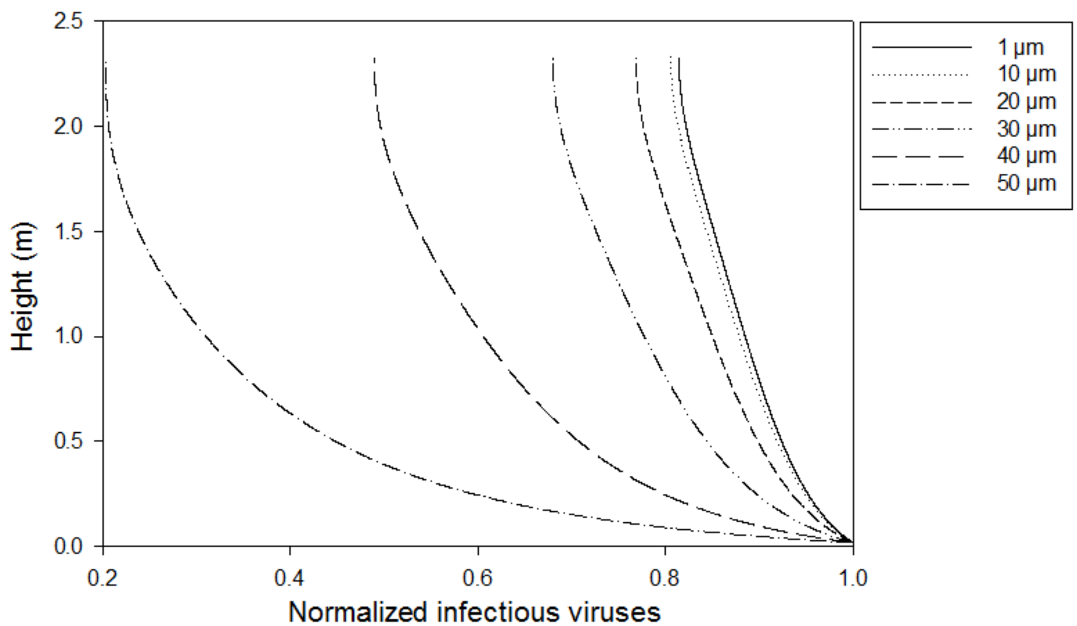
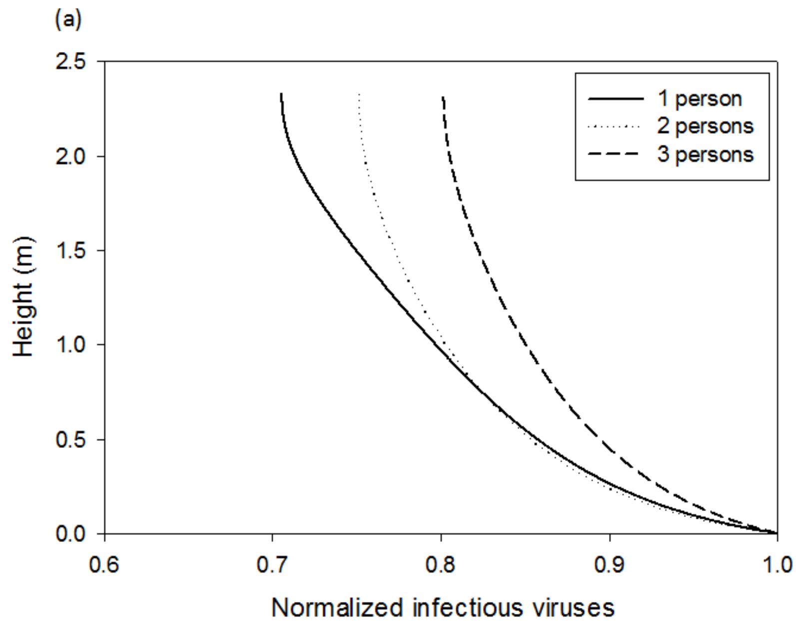


Figure 8. Concentration of infectious viruses as a function of height, normalized to the concentration at ground level at (a) 15% RH and (b) 95% RH.



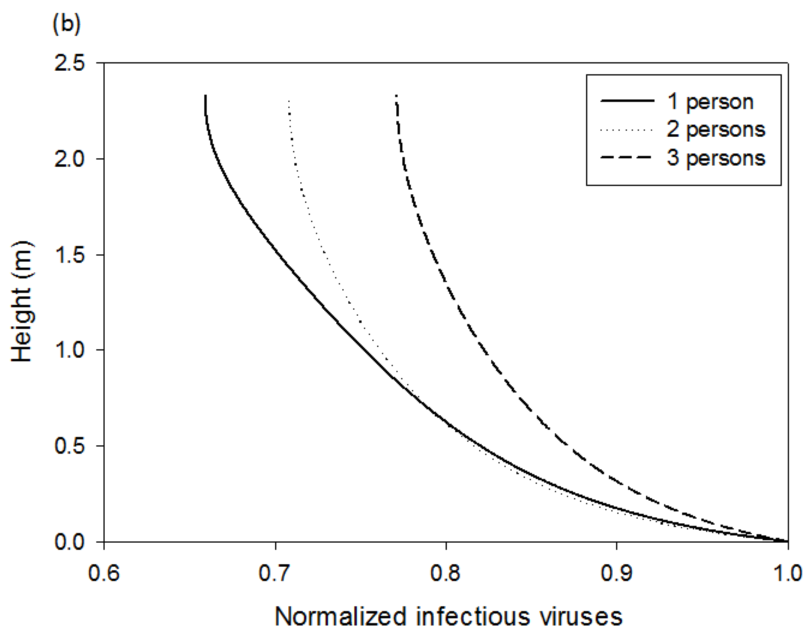


Figure 9. Normalized vertical concentration profile of total resuspended viruses at (a) 15% RH and (b) 95% RH.

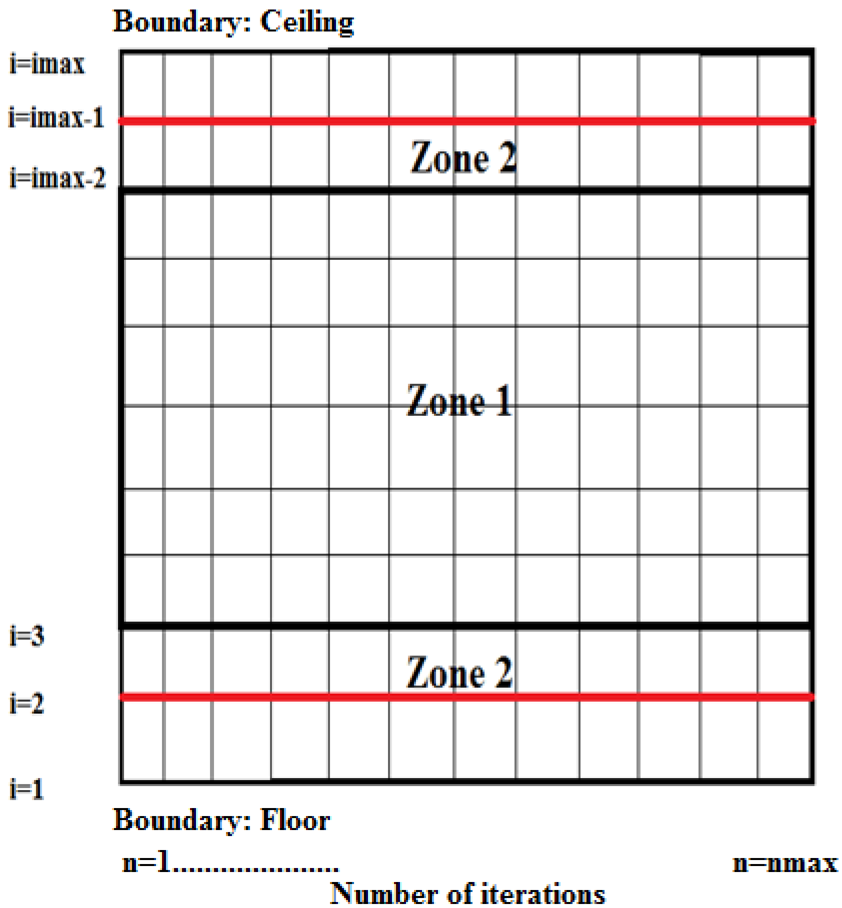


Figure S1. The numerical grid space used for simulation of concentrations. The grid is divided into 128 nodes in the vertical direction and traverses through iterations along the horizontal direction until the concentration at each node reaches its steady-state value.

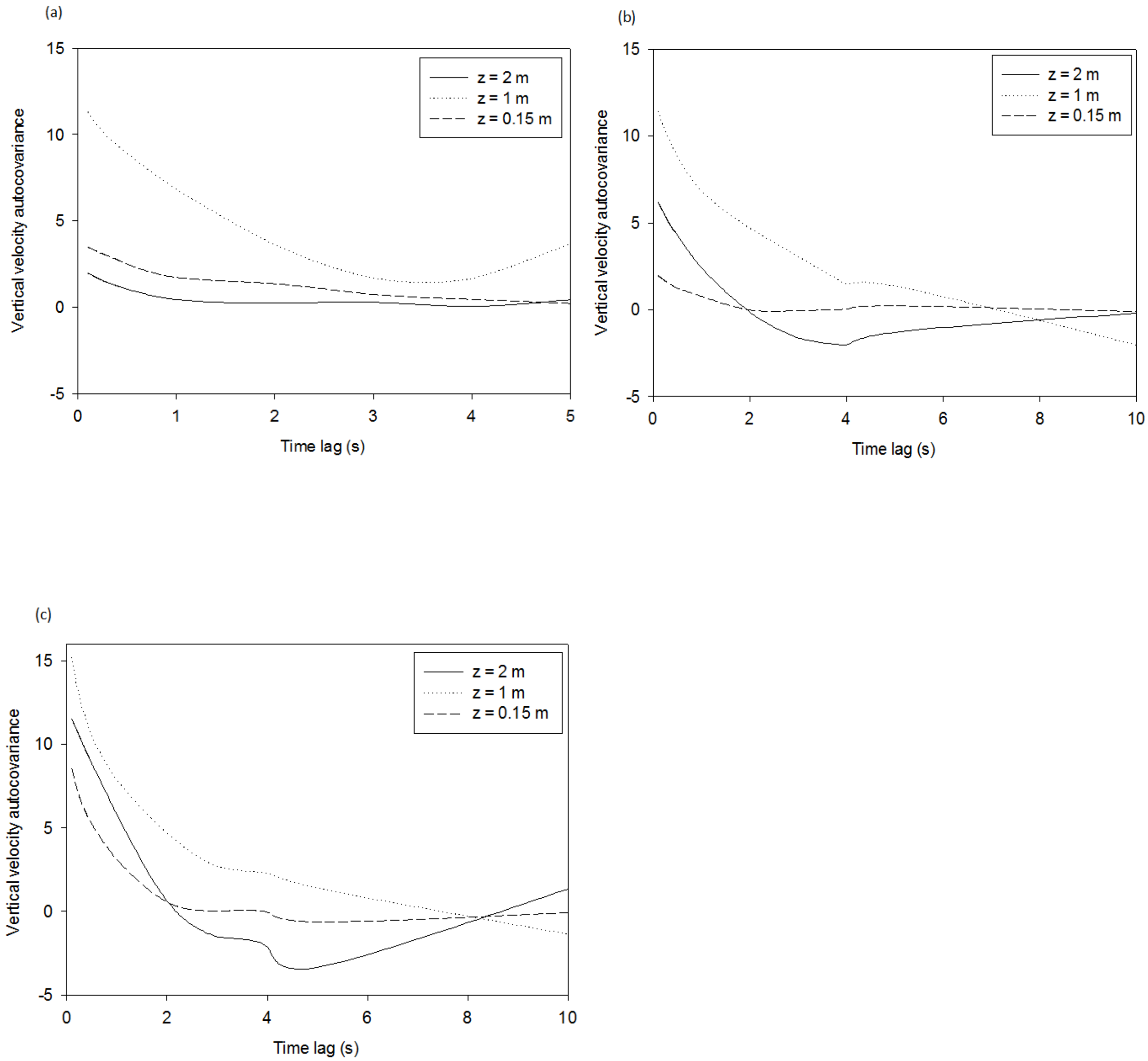
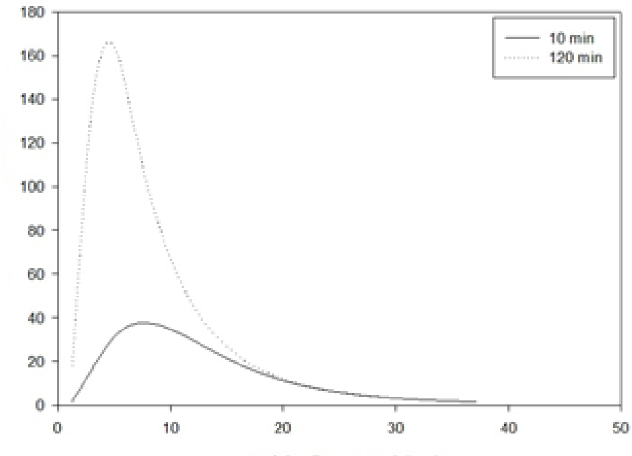
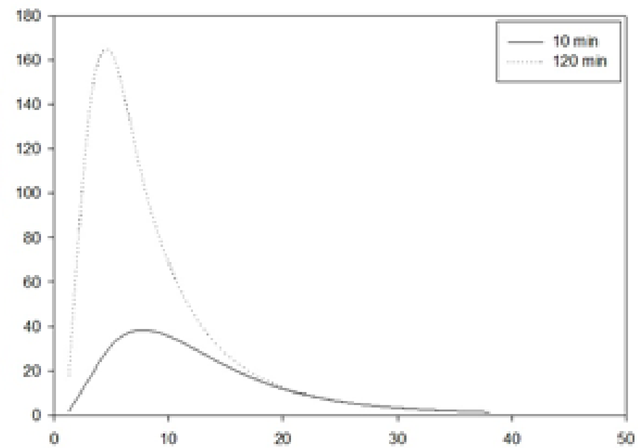


Figure S2. Vertical velocity autocovariances at three heights for (a) 1 person walking, (b) 2 persons walking, and (c) 3 persons walking in the patterns shown in Figure 1.

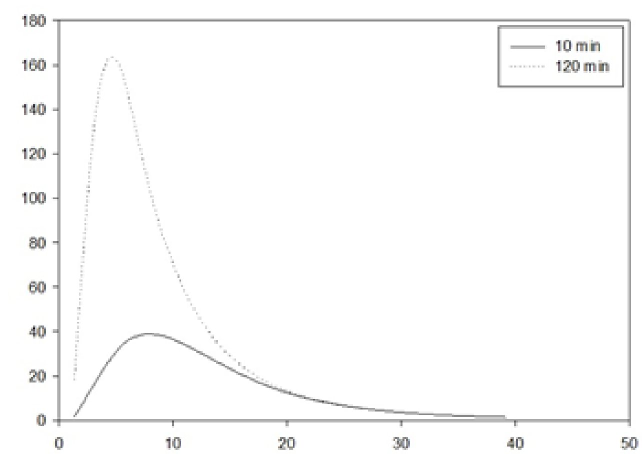
Number of particles (# particles m^{-2} / Δd)



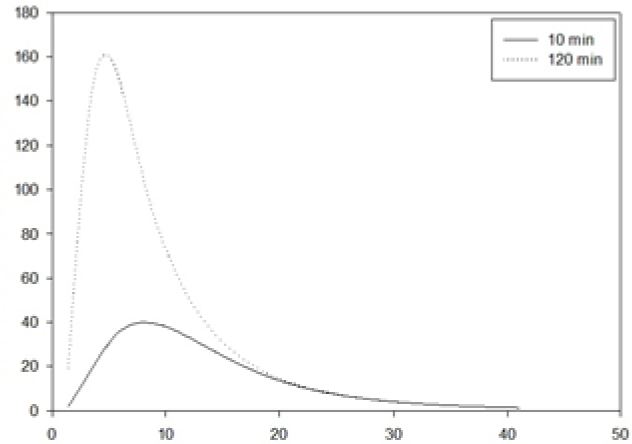
(a)



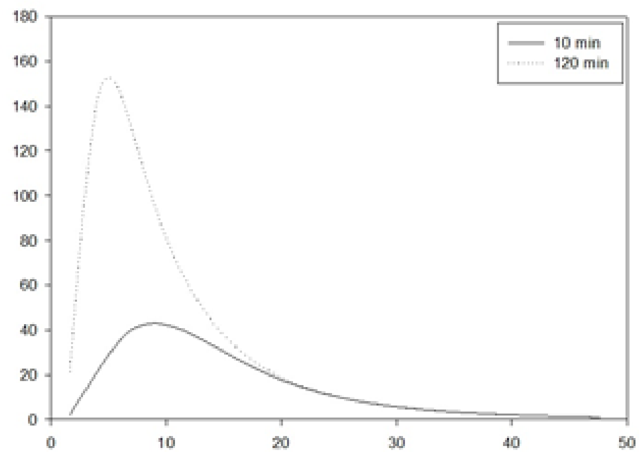
(b)



(c)



(d)



(e)

Particle diameter, d (μm)

Figure S3. Number of particles (carrier particles, not just viruses) in the floor dust per unit area at (a) 15% RH, (b) 35% RH, (c) 55% RH, (d) 75% RH, and (e) 95% RH.

Chapter 3. Practical Implications

A person with influenza is likely to emit virus-laden particles into the air during coughing, sneezing, talking, or breathing, and some fraction of these will deposit on the floor. Forces generated by walking can resuspend the particles and create higher concentrations close to the floor and lower concentrations above it. Thus, shorter people may be exposed to higher concentrations of viruses that are resuspended from the floor. The same conclusion applies to resuspended floor dust in general, including toxic compounds, and other pathogens. This work could be used in support of epidemiological investigations into the incidence of influenza as a function of a person's height and to guide the design of more effective control strategies to reduce transmission of influenza.

Chapter 4. Future work

This study is the first step towards understanding the vertical concentration gradient of resuspended viruses due to indoor human activities. The numerical simulations performed in this research are based on the experimental measurements of the turbulent flow field generated during human movement in the room. However, the reported concentration gradients should be experimentally validated. Future studies could aim at making real time measurements of the viral particle concentration gradient across a room's height during walking.

Researchers should also look into the resuspension rate of large particles. We assumed the resuspension rate to be directly proportional to the particle size up to 50 µm. While previous studies have shown the resuspension rate to be directly proportional to the particle size in the range of 1-20 µm, resuspension of particles measuring up to 50 µm is yet to be studied.

The effect of ventilation air currents on the vertical concentration gradient of the resuspended particles needs to be investigated. We hypothesize that in a well-ventilated indoor environment, air flow could regulate the vertical concentration gradient by carrying the particles away from or towards the floor.

The effect of indoor relative humidity on the resuspension of particles less than 10 µm has been studied in the past. However, the impact of RH variation on the resuspension rate of large particles is yet to be measured experimentally. Also, probing is required to understand the effect of a person's height and foot size on vertical concentration gradient of resuspended floor dust.

Appendix: Numerical code

```
Integer n, i
      Parameter (imax=129)
      Parameter (niter=100000)
      Integer                    ::  psn=1
      Real                       ::  CFL=0.1
      Real                       ::   L=2.35
      Real                       ::   delx
      Real                       ::  delt
      Real                       ::  Vd
      Real                       ::  d= 1.27
      Real                       ::  g= 9.81
      Real                       :: pden= 2.68E+03
      Real                       :: Kn
      Real                       :: cc
      Real                       :: vis= 1.85E-05
      Real                       :: a,b,c1,d1
      Real                       :: e,f,g1,h1
      Real                       :: p,q,r,s1
      Real,Dimension(imax)              ::  S  !Source term
      Real,Dimension(imax)              ::   h
      Real,Dimension(imax)              ::     k=99.9
      Double Precision ,Dimension(niter,imax)          ::     C=99.9
      Double Precision ,Dimension(niter,imax)          ::   res=99.9

      Open(1,File='partcle1pnew15RH10min1.27ck.dat',Status='Unknown')
      Open(2,File='newresidual.dat',Status='Unknown')
C     Open(3,File='time.dat',Status='Unknown')
```

```
C      Define Constants
        delx=L/(imax-1)
        delt=CFL*0.5*delx

C      CALCULATION OF DEPOSITION VELOCITY
        If(d.LE.5.0)Then

C      PARTICLE WILL SLIP BETWEEN THE MOLECULAR SPACES AND SO APPLY
SLIP CORRECTION FACTOR
       Kn=2*0.065/d
       cc=1+Kn*(1.257+0.4*Exp(-1.10/Kn))
       Vd=(g*(d*1.0E-06)**2)*pden*cc/(18.0*vis)



       Elseif(d.GT.5.0)Then

C      NO SLIP CORRECTION FACTOR REQUIRED

       Vd=(g*(d*1.0E-06)**2)*pden/(18.0*vis)

       Endif

C      Set the source term

       Do 20 i=2,imax
       S(i)= 0.0

20     Continue

       S(1)= 1.5E-06 !node i=1 is on the floor. S has a fixed value on it.
```

```
C      SET BOUNDARY CONDITIONS

       k(1)=0.0
       k(imax)=0.0
       h(1)=0.0


C       SET INITIAL CONDITIONS

       Do i=1,imax !Concentration on all the nodes except the floor is zero.

       C(1,i)= 00.0

       End do
C      CALCULATE HEIGHT FROM THE FLOOR FOR EACH NODE 'i'

       Do i=2,imax
       h(i)=h(i-1)+delx
       End do
C      !EDDY DIFFUSION COEFFICIENT CHANGING WITH HEIGHT IS GIVEN BY...

       If (psn.eq.1)then
       Do i=2,imax-1
         k(i)= 0.0648*(h(i)**3.0)-0.2749*(h(i)**2.0)+0.2946*h(i) +0.0417
          End do
       Else if (psn.eq.2) then

       Do i=2,imax-1
       k(i)= 0.0401*(h(i)**3.0)-0.1929*(h(i)**2.0)+0.2598*h(i)+0.0329
       End do
```

```
      Else if (psn.eq.3) then
       Do i=2,imax-1
 k(i)= 0.0462*(h(i)**3.0)-0.2314*(h(i)**2.0)+0.3107*h(i)+0.0615
       End do
             End if

!!!!!!!!!!!!!!!!!Main Body!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

       Do 10, n=1,niter

C      CALCULATE CONCENTRATION FOR NODE i=1   !Near the floor
       a=(Vd*delx/2.0)*(4.0*C(n,2)-3.0*C(n,1)-C(n,3))
       b=k(1)*(2.0*C(n,1)-5.0*C(n,2)+4.0*C(n,3)-C(n,4))
       c1=0.25*(4.0*k(2)-3.0*k(1)-k(3))*(4.0*C(n,2)-3.0*C(n,1)-C(n,3))
       d1=S(1)*(delx**2.0)

       res(n,1)=(delt/(delx**2.0))*(a+b+c1+d1)
       C(n+1,1)=C(n,1)+res(n,1)
C      CALCULATE CONCENTRATION FOR NODE i=imax   !Near the ceiling
       e=(Vd*delx/2.0)*(3.0*C(n,imax)-4.0*C(n,imax-1)+3.0*C(n,imax-2))
       f=k(imax)*(2.0*C(n,imax)-5.0*C(n,imax-1)+4.0*C(n,imax-2)
     &    -C(n,imax-3))
       g1=0.25*(3.0*k(imax)-4.0*k(imax-1)+3.0*k(imax-2))*(3.0*C(n,imax)
     &    -4.0*C(n,imax-1)+3.0*C(n,imax-2))
       h1=S(imax)*(delx**2.0)
      res(n,imax)=(delt/(delx**2.0))*(e+f+g1+h1)
       C(n+1,imax)=C(n,imax)+res(n,imax)

C      CALCULATION ON THE NODES i=2 and i=imax-1
       Do i=2,imax-1
```

```
      p=(Vd*delx)*(C(n,i)-C(n,i-1))
      q=k(i)*(C(n,i+1)-2.0*C(n,i)+C(n,i-1))
      r=(k(i+1)-k(i))*(C(n,i+1)-C(n,i))
      s1=S(i)*(delx**2.0)
      res(n,i)=(delt/(delx**2.0))*(p+q+r+s1)
      C(n+1,i)=C(n,i)+res(n,i)
      End do

C     WRITE THE OUTPUTS
      Write(1,25)(C(n,i),i=1,imax)
      Write(2,25)(res(n,i),i=1,imax)
25    Format(2X,129E15.6)
10    Continue

      Close(1)
      Close(2)
      Stop
      End
```