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A New Approach for Respiratory Droplet Trajectory: Implications for Viral and Bacterial Disease Transmission in Emergency Departments

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ABSTRACT

Background The objective of this study is to devise a simplified approach for estimating respiratory particle trajectory to avoid infection in gathering places of emergency departments.

Methods To the authors' knowledge, no sufficient/obvious data exist on lateral routes of disease transmission through respiratory droplets along the *x*-axis. The present study establishes a preliminary baseline approach based on the upper pharynx-mouth geometry for lateral social distancing to protect susceptible persons from the droplets of an infected person. An enhanced version of ART (Aydin's Research Team) model has been employed as a supplementary tool of Stokes's law for quantification of motion dynamics of the virus/bacterium-laden droplets in public indoor places.

Results A range of droplet diameters varying from 1 μm to 2000 μm were considered in this study. The droplets with a diameter of ≤ 22.5 μm can completely evaporate during settling and droplet nuclei can remain in the air for extended periods. An individual *Influenza* virus can stay airborne for 34.4 days, while a single *Streptococcus* bacterium remains suspended for 18.6 hours. The proper social distancing between infected and healthy persons should be about 2.9 and 0.9 m longitudinally, and 0.45 and 0.15 m laterally based on the novel aspects of the present study for sneezing/coughing and breathing/talking, respectively. The trajectory of respiratory particles in the streamwise and radial directions resembles the shape of a truncated cone due to the upper pharynx-mouth relationship.

Conclusion The outcomes of this study can help further understanding of respiratory particle trajectory, thereby improving measures to mitigate disease transmission.

Key words droplet evaporation; indoor environment; lateral trajectory; microbial spread; Stokes and ART models

Mathematical modeling of disease transmission has been a long-standing research topic and respiratory particle trajectory plays a very important role in the spread of diseases under indoor and outdoor conditions.[1–4] For example, *Influenza* viruses and *Streptococcus* bacteria are two important pathogens that pose a risk to people in high-traffic areas of emergency departments. Infected individuals can spread diseases through respiratory particles when they breathe, talk, cough, and sneeze. The location of a person with respect to the infected individual plays an important role in direct contamination. Direct contamination is significantly impacted by a person's proximity to the infected person. However, the persons directly facing the infected individual may have a higher risk of the infection through direct contamination than the person standing next to him/her.

Intensive and time-consuming studies are being conducted on the necessary precautions to protect people from the airborne infections and harmful particles.[5] Therefore, the mechanisms of transmission through respiration need to be understood very well. Firstly, we searched for the current knowledge about the transport dynamics of expiratory particles containing pathogens. In this subject, numerous excellent studies have been carried out to give detailed information on the physical and/or mathematical aspects of motion dynamics of respiratory particles. For example, a dynamic and comprehensive model has been built by Wang et al.[6] to quantitatively investigate the transport and the lifetime of respiratory droplets as virus carriers. The trajectory and/or evaporation of expelled droplets have been studied by different researchers. Klaseboer et al.[3] investigated the trajectory and evaporation of respiratory droplets by comparing numerical simulations with experimental data. Aydin et al.[7] developed a simple equation based on experimental data indirectly to compute droplet evaporation. Likewise, the evaporation

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rates of droplets were experimentally determined by Chaudhuri et al.[8] There are some incompatibilities among the experimental data of different studies. These discrepancies may be attributed to the experimental methods used in those investigations.

Stokes's law is a fundamental equation of fluid dynamics and its various modifications have been set forth.[9] For example, the original Navier-Stokes equations require supercomputers. Instead, the average velocity and pressure in the time are obtained using the Reynolds-averaged Navier–Stokes approach.[10, 11] In this aspect, the relationships between drag coefficients and Reynolds' numbers can be found in the literature.[10, 12–14] Most studies on the dynamics of respiratory particles use computational fluid dynamics (CFD) technique to solve complex problems based on numerical calculations and algorithms.[13] Although the CFD technique has a lack of generic predictive power, it is useful in particular situations.[15] Similarly, many researchers have utilized the CFD models to assess social distancing feasibility in different environments, considering the risks for airborne transmission.[11, 15–18] However, it is not easy to accurately assess the full effects of environmental conditions on the spread of diseases,[3] since interactions inside the turbulent space result in a dynamic as well as chaotic flow pattern that varies with both location and time. Aydin & Savas[9] reported that the published models for motion dynamics of expiratory particles have been based on varying assumptions and include certain limitations. As a result, some findings from those studies do not allow us to conclude an objective decision.

Under gravitation, the pathogen-laden droplets gain a downward terminal speed (in the z-direction) which can be determined by Stokes's law.[19, 20] Similarly, respiratory particle motion in the jet flow route (in y-direction) can easily be calculated by use of the free fall model.[6, 20–22] However, the movement of particles in the lateral (x) direction was not clearly quantified in previous studies. Nevertheless, the microbial spread from person to person can also happen laterally. Even more importantly, despite numerous investigations dealing with the quantification of the proper social distancing,[6, 10, 21–24] there is insufficient quantitative knowledge to predict conservational or safety distance in lateral directions among people.

There are different approaches for determining the horizontal travel distance of a particle from the source (i.e., the mouth) in the jet flow direction.[6, 20] For example, Wang et al.[6] schematized the jet flow fields based on mouth width and jet velocity at the mouth exit. Similarly, Wang et al.[14] investigated the trajectories of respiratory particles in the streamwise and radial directions, and observed that the streamwise velocity followed a Gaussian distribution. It is known that the Gauss function profile is compatible with experimental data. Although those studies have taken the human height and mouth position/diameter into account, they have only considered the motion dynamics after the respiratory particles exit the mouth and/or nose. In other words, the aerodynamics and trajectory of pathogens-laden respiratory droplets in indoor and outdoor spaces are generally assessed after the particles are released from the mouth.[6, 13] However, the trajectory of respiratory particles is also determined by the upper pharynx-mouth-nose geometry in addition to the air conditions.

The goal of this study was to estimate the motion dynamics of the *Influenza* virus and/or *Streptococcus* bacterium-laden respiratory droplets along with their evaporation in the gathering places of emergency departments for the four-dimensional (three-dimensional space and time) dissemination. This is the first study that determines the lateral trajectory of respiratory particles based on the upper pharynx-mouth geometry, especially. In addition, an enhanced version of the ART (Aydin's Research Team) model proposed by Aydin & Savas[9] has been employed as a supplementary tool of Stokes's law for quantification of the motion dynamics of the virus/bacterium-laden droplets in public indoor places.

MATERIALS AND METHODS

Pathogens

The flu is an acute respiratory illness caused by influenza viruses and the *Influenza A* virus is responsible for most cases of severe illness. It can infect people of all ages, and at times can lead to death. The virus particle may be spherical-shaped, and its size is about 120 nm (1 nm = 10^{-9} m).[25] Infected people can transmit *Influenza* viruses through respiratory droplets released by breathing, talking, coughing, and sneezing.

On the other hand, *Streptococci* can also cause illness transmission in emergency departments. *Streptococcus* contains a variety of species: For example, *Streptococcus pneumonia* (*pneumococci*) and *Streptococcus pyogenes* (group A *streptococci*) are found in the human nasopharyngeal flora and transmitted from person to person through the respiratory tract as well as expiratory particles in the air. They vary widely in pathogenic potential and can cause diseases ranging from upper respiratory tract infections to fatal diseases including pneumonia, meningitis, sepsis, and endocarditis. *Streptococci* can be mortal in emergency departments and intensive care units, particularly in immunosuppressed patients. *Streptococcus pneumonia*

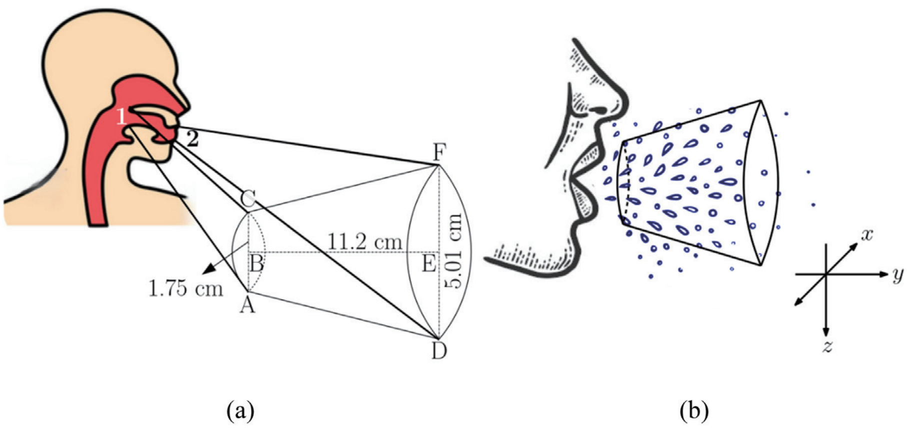


Fig. 1. Upper pharyngeal and mouth airway spaces of a virtual human: (**a**) the used geometry between upper pharynx (1) and mouth (2) (AC = Upper pharyngeal width, DF = Mouth width, BE = Distance between upper pharynx and mouth), (**b**) an infected person emitting respiratory droplets.

is usually lancet-shaped, and it appears as a 0.5–1.25 µm diplococcus in diameter. *Streptococcus pneumonia* is the most common bacterial agent of pneumonia and meningitis in adults. On the other hand, its infections can take the form of empyema, otitis media, sinusitis, conjunctivitis, septic arthritis, peritonitis, endocarditis, and sepsis. *Streptococcus pyogenes* is an important bacterial pathogen with a diameter of 0.6–1.0 µm. Its most common bacterial agents are tonsillitis and pharyngitis. Additionally, *Streptococcus pyogenes* can result in otitis media, mastoiditis, empyema, myositis, necrotizing fasciitis, meningitis, and endocarditis. Its most common infections at the skin are impetigo, cellulitis, and erysipelas. It is a leading cause of scarlet fever. It is also a major cause of osteomyelitis, which is a serious infection of the bone, and arthritis. Some species may cause rheumatic fever and acute post-streptococcal glomerulonephritis. It is found in the nasopharyngeal flora of healthy people and can cause disease, especially after viral infections.[26] *Neisseria* species are gram-negative cocci with a diameter of 0.6 to 1.0 µm. These bacteria are usually seen as diplococcus with the adjacent sides flattened. *Neisseria meningitis* is the agent of acute bacterial meningitis with high mortality. *Neisseria meningitis* infection results from the bloodborne dissemination of the meningococcus due to a nasopharyngeal carrier state or rhinopharyngitis.[27]

In this study, the *Influenza* virus and *Streptococcus* bacterium were treated as single spherical particles, with average diameters of 120 nm[25] and 0.8 µm[26, 27] respectively; and with a protein density of 1.35×10^3 kg/m^3.[1]

Model description

It appears that no satisfactory data currently exist on the lateral (*x*-axis) transmission pathways of respiratory particles. In this study, therefore, the upper pharynx-mouth dimensions were considered to determine the lateral trajectory of respiratory particles, mainly. The present study establishes a preliminary baseline approach for lateral social distancing in indoor environments. Figure 1 illustrates the used geometry in the model between upper pharyngeal width and mouth width in different adult populations. Another way to phrase it, this geometrical sub-model is based on data available in the literature: The mean upper pharyngeal width is 1.75 cm[28] while the mean mouth width is 5.01 cm.[29] On the other hand, the average value of maximum mouth opening is 4.84 cm.[30] In addition, the average distance between the upper pharynx and the mouth is about 11.20 cm for adults.[31, 32]

We have quantified motion dynamics of the pathogens-laden droplets in closed spaces and/or the gathering places of emergency departments for the four-dimensional (3D space + time) spread. A range of droplet diameters varying from 1 µm to 2000 µm were considered in this study, although most of the respiratory droplets -which may contain viruses/bacteria- are in the range of 1–100 micrometers.[8] However, the number of inhaled droplets, the concentration of which decreases as the distance from the patient increases, was not considered.

The volume (*vol*, in m^3) and mass (*m*, in kg) of the spherical particles can be calculated from simple parameters in the following ways[20]:

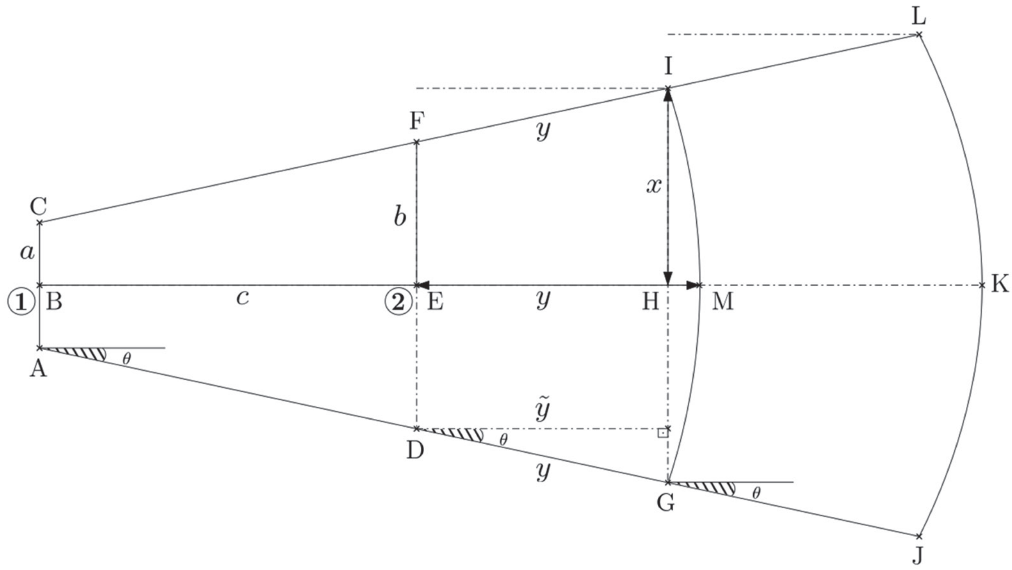


Fig. 2. Schematization of the flow pattern of expiratory particles in the lateral (*x*) and the jet flow (*y*) directions (|AD| = |CF|, |DG| = |EM| = |FI|, |DJ| =|EK| = |FL|).

$$vol = (4/3)\pi r^3 \quad (1)$$

$$m = \rho_p (4/3)\pi r^3 \quad (2)$$

in which r and ρ_p represent the particle radius (m) and density (kg/m^3), respectively.

The settling time (t_f, in seconds) and the horizontal distance (y, in m) from the mouth in the jet flow direction of a particle in free fall can be determined as[20]:

$$t_f = \sqrt{\frac{2z}{g}} \quad (3)$$

$$y = v_o t_f = v_o \sqrt{\frac{2z}{g}} \quad (4)$$

here, z is the vertical falling distance or height above the ground (taken as 1.7 m); g is the acceleration due to gravity (9.81 m/s^2); and v_o is the initial velocity of the particle (m/s).

Eq. (4) may have a strong bias, but it provides a rough guideline at best in practice. In Newtonian physics, this equation is the simplest one where gravity is only the force that acts on a settling particle; and the effects of drag force, virtual mass, pressure gradient force, and air turbulence are ignored. However, this is a useful tool and based on reasonable as well as simplistic assumption (within the limitation of the model) to roughly compute travel distance from the mouth in the jet flow direction, since the movement of respiratory particles > 80 μm (in diameter) is governed by gravity.[13] The main flaw of this model is that it cannot calculate the transport distance of a single particle with a specific diameter.

From Fig. 2 (based on Fig. 1), the following relation among lengths can be written:

$$\frac{|BH|}{|BE|} = \frac{|GI|-|AC|}{|DF|-|AC|} \quad (5)$$

With the adopted labels in Fig. 2, Eq. (5) can be re-arranged:

$$\frac{\tilde{y}+c}{c} = \frac{x-a}{b-a} \quad (6)$$

Solving for x, Eq. (6) yields:

$$x = \frac{b-a}{c}\tilde{y} + b \quad (7)$$

Based on geometrical rules for triangles, the following equation can be introduced:

$$\tilde{y} = y\cos\theta \quad (8)$$

Eqs. (7) and (8) can be combined as:

$$x = \frac{b-a}{c} y \cos\theta + b \quad (9)$$

It can easily be inferred from Fig.2 that the distances |EM| = y and |EH| = $\tilde{y}$. Similarly, the variation in the transmission distance in the lateral direction (x) can be expressed with respect to the horizontal distance from the mouth (y). If the upper pharyngeal width is $2a$ = 1.75 cm, the mouth width is $2b$ = 5.01 cm, and the distance between the upper pharynx and the mouth is c = 11.2 cm (see Fig. 2), then Eq. (9) simplifies to

$$x = 0.1455\, y \cos\theta + 2.505 \quad (10)$$

Note that with the dimensions given above, $\tan\theta = \left[\frac{5.01-1.75}{2}\right]/11.2$, therewith $\theta \approx 8.28°$.

In this study, we assumed the mouth width to be 5.01 cm.[29] In another study,[13] the mouth width during sneezing was assumed to be 4.0 cm to conduct the necessary simulations for sneezing. The shape or dimensions of the throat and mouth vary according to genetic makeup, gender, and age. Here, the application of Eq. (9) suggested in this manuscript is the main goal.

Under conditions of terminal or constant falling velocity, Stokes's law[20] can be applied (for droplets with diameters ≤ 50 µm) to ascertain the downward velocity (v_z, in m/s):

$$v_z = \frac{2r^2 g}{9\eta}(\rho_p - \rho_a) \quad (11)$$

In the above equation, r is the particle radius (m); ρ_p is the particle density (kg/m^3); ρ_a is the air density (1.2041 kg/m^3 at 20 °C and 1 atm); and η is the dynamical viscosity of air (1.85 × 10^{-5} kg/(m s)).

As is known, Stokes's law (Eq. 11) is obtained by equating the weight of a spherical particle with the upward drag force. In other words, the effects of viscous drag are considered, while the effects of inertial drag are ignored. Therefore, the use of the traditional Stokes model has been limited to the situations of low Reynolds' number in this study. In addition, the effect of slippage becomes significant when particle diameters become smaller than 5 µm.[12]

The enhanced ART (Aydin's Research Team) model can serve as a complementary tool to Stokes's law for analyzing the transport dynamics of droplets with diameters ≥ 50 µm in indoor environments[9]:

$$v_z = \frac{\sqrt{mg}}{2\pi r}\left(\sqrt{\frac{2\pi}{\kappa\rho_a}} + \frac{\sqrt{mg}}{6\eta}\right) \times 0.1 \quad (12)$$

in which, m represents the mass of the falling object (kg), $\pi \approx 3.1416$, and κ is a coefficient depending on the particle shape (κ = 0.47 if spherical). The time (t_z, in seconds) for particles to fall from a specified height in calm air can therefore be found as follows[7]:

$$t_z = z / v_z \quad (13)$$

In the ART model (Eq. 12), the resisting force due to friction, the downward force due to gravity, and the lift force have been combined with another mathematical operation.[7, 20]

It is better to consider droplet evaporation when pathogens are transmitted via respiratory droplets in the air.[33] The droplet evaporation for indoor conditions can be predicted from measurable parameters. Using air temperature and relative humidity, Aydin et al.[7] estimated droplet evaporation by the following equation:

$$E_i = 4\left(0.364\exp(0.084T_a) + 3.64\exp(-0.021H_r)\right) \quad (14)$$

where E_i represents the indoor droplet evaporation rate (mm/day), T_a denotes the daily mean air temperature (ranging from 2 to 49°C), and H_r indicates the relative humidity (ranging from 10 to 90%).

Overall, the output of the models should be realistic but at the same time concise for practical interest. In more detailed studies, the effects of diverse forces (such as gravity, Brownian, Saffman, viscous/inertial drag, and pressure gradient forces), initial position, virtual mass, evaporation and/or coalescence of the droplets, air turbulence, and convective airflow (and so on) should be considered. However, there is no simple approach that is likely to be applicable to all situations, and to consider all relevant factors; because various factors contribute to a highly complex (chaotic) flow pattern. In this study, the primary concern is to obtain the variables/parameters required for Eq. (9) in a convenient way, although Eq. (4) has some limitations due to several associated assumptions.

RESULTS

As a one-way flux (x = 0, y = 0, and z = 1.7 m), the calculated settling velocities of respiratory droplets as a function of their diameters are presented in Fig. 3. The velocity of droplets exhibited exponential growth with its rising diameter.

The computed settling durations of the expiratory

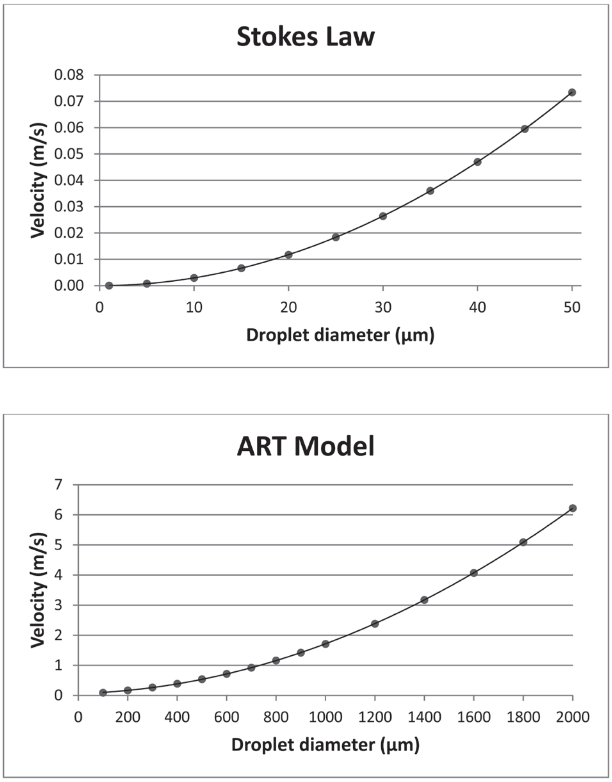


Fig. 3. Falling velocity of respiratory droplets as estimated from the Stokes's law and the ART model.

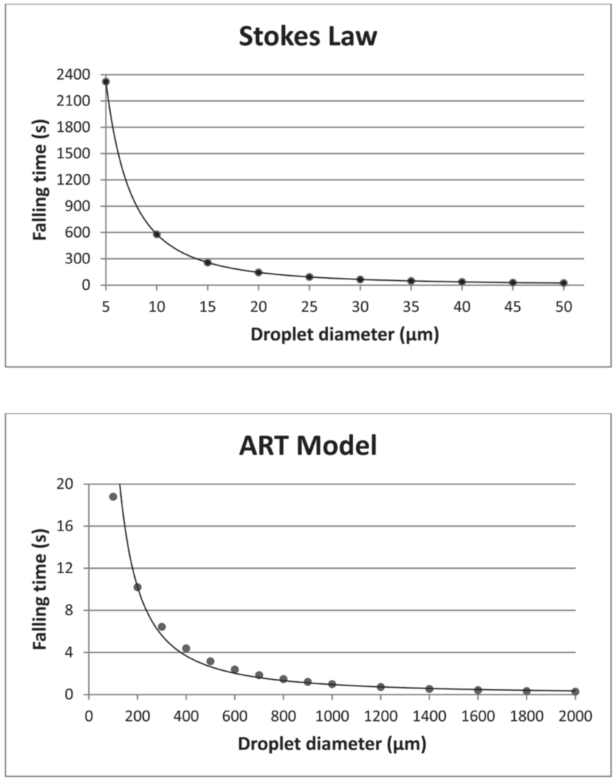


Fig. 4. Settling time of respiratory droplets from 1.7 m height to the ground.

droplets with varying sizes from a height of 1.7 m to the ground are shown in Fig. 4. The results clearly illustrate that the Stokes and ART (Aydin's Research Team) models predicted reasonable settling times. Using Stokes's law for droplets with diameters ≤ 50 μm, the falling times ranged from 16.1 hours for a droplet size of 1 μm to 23.2 s for a droplet size of 50 μm. The ART model, which was used for the droplets larger than 50 μm, predicted that droplets could reach the ground from a height of 1.7 m between 18.8 s (100 μm diameter) and 0.27 s (2000 μm diameter).

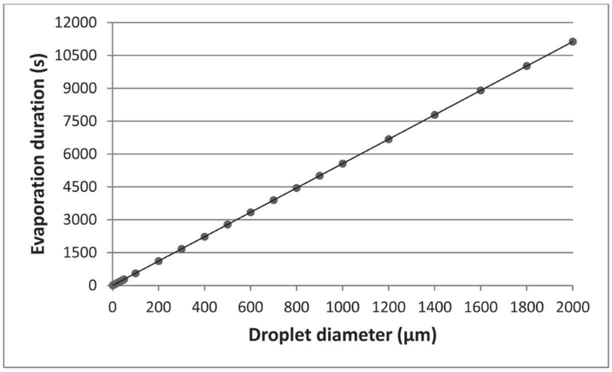
The estimated evaporation duration of the droplets is presented as a function of droplet diameter in Fig. 5a. In this work, the effects of two variables, namely temperature and relative humidity (H_r), on indoor evaporation were only taken into consideration. The room temperature and H_r were assumed as 22 °C and 40%, respectively, for the estimates of evaporation. The evaporation duration increases with increasing droplet size. As emphasized by Wang et al.[6] the lifetime of respiratory droplets is a key parameter. To further determine whether the falling time of a pathogen-laden droplet from a specific height is shorter or longer than its evaporation time, a comparison of falling and evaporation times of respiratory droplets for a limited range of diameters is illustrated in Fig. 5b. The intersection point of the two curves was between 20 and 25 μm in droplet diameter. The evaporation duration of smaller droplets is shorter than the falling time.

A comparative quantification of the *Influenza* virus, *Streptococcus* bacterium, and a respiratory droplet is given in Table 1. Pulit-Penaloza et al.[34] have described the characteristics of *Influenza* viruses and their transmission and reported that sufficient *Influenza* viruses remained viable in the air and could cause infection, even after 30 min of aging. Similarly, Oswin et al.[35] have studied the airborne longevity of group A *Streptococcus* and demonstrated that approximately 70% of bacteria remained viable after 20 min of levitation at 50% relative humidity.

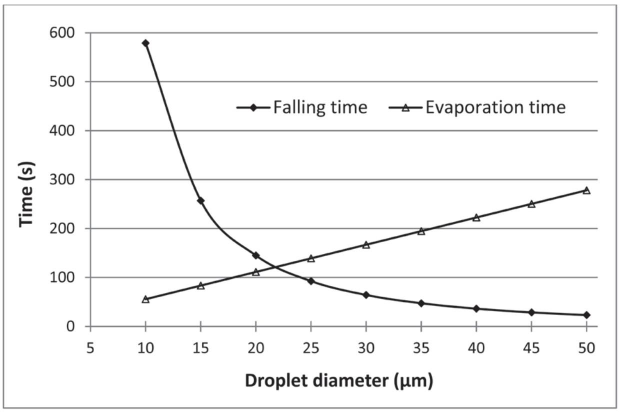
The initial velocity-dependent trajectory of droplets in the jet flow (y) and lateral (x) horizontal directions can be observed in Table 2 and partially from Fig. 6. They visualize droplet transport distances in both directions.

DISCUSSION

Apparently, there is no data on the number of pathogens released with each respiratory droplet from an infected person. It was assumed that a droplet encapsulated a



(a)



(b)

Fig. 5. Evaporation duration of respiratory droplets in an indoor environment: (**a**) evaporation time of a droplet of 1 to 2000 µm in diameter, (**b**) comparison of falling and evaporation times of respiratory droplets for a limited range of diameters.

single pathogen, although not all respiratory droplets would carry a pathogen but part of them could.[22] For the initial spatial coordinate of the droplet, we apply $x = y = 0$ m, and $z = 1.7$ m, where the droplet is released from the mouth/nose. The results from Stokes's law showed that the settling velocities ranged from 2.94×10^{-5} m/s (for a droplet with 1 µm diameter) to 7.34×10^{-2} m/s (for a droplet with 50 µm diameter). The velocity of larger droplets was estimated using the ART model, since Stokes's law does not appear to be applicable for droplets > 50 µm.[16] The outputs of the ART model exhibited a range of the falling velocity of 9.06×10^{-2} m/s (droplet with 100 µm in diameter) to 6.22 m/s (droplet with 2000 µm in diameter). The velocity of droplets showed exponential growth with its rising diameter in both models (Fig. 3).

Ugarte-Anero et al.[13] indicated that the motion dynamics of particles smaller than 30 µm (in diameter) is subjected to the Brownian effect. The particles up to 80 µm are affected by diverse forces, while larger particles are dominated by the gravitational force. This means that the gravity force dominates over the other forces for the large particles.[36]

The results predicted by Stokes's law showed a wide range of droplet falling times, from 5.79×10^{4} s (16.1 hours) to 23.2 s, depending on droplet size (see Fig. 4). The ART model accurately describes the falling times of droplets larger than 50 µm, revealing that the falling time varied between 18.8 s for a droplet size of 100 µm and 0.27 s for a diameter of 2000 µm under the conditions of calm air. The predictions of Stokes and ART models were consistent for the falling times, as was previously reported by Aydin & Savas.[9]

Micro-scale droplets can evaporate quickly under the conditions of low to moderate relative humidity, as noted by Anchordoqui & Chudnovsky[19] Aydin et al.[1, 7] and Wang et al.[6] The evaporation duration of droplets exhibited a linear increase with their diameter and the evaporation time of smaller droplets was shorter than their falling time (Fig. 5). In this study, the determined evaporation times of the droplets were found to be considerably longer than some experimental[3, 8] or calculated[13, 18, 37] data given in the literature. It is worth mentioning that the equation used in this study was developed indirectly based on experimental data.[7]

Table 1. Comparison of falling velocity and duration of virus, bacterium, and a droplet with 1.0 µm diameter in the calm air based on Stokes's law

Object	Average diameter (µm)	Mass (µg)	Settling velocity of object in the calm air (m/s)	Settling duration of object from 1.7 m height to the ground		Longevity of pathogens at moderate H_r and temperature	Evaporation duration of droplet at 40% H_r and 22 °C
				day	hr	min	s
Influenza virus	0.12[(a)]	1.22×10^{-9}	5.72×10^{-7}	34.4		30[(b)]	
Streptococcus	0.8	3.62×10^{-7}	2.54×10^{-5}		18.6	20[(c)]	
Droplet	1.0	5.23×10^{-7}	2.94×10^{-5}		16.1		5.6

[(a)]*Dadonaite et al.*,[25] [(b)]Pulit-Penaloza et al.,[34] [(c)]Oswin et al.[35]

Table 2. Transport distance of expiratory particles in the lateral (*x*) and the jet flow (*y*) directions as a function of initial velocity (v_o) (Height from the ground (*z*) was taken as 1.7 m)

Action	Initial velocity (m/s)	Travel distance from mouth (*y*) in jet flow direction (m)	Longitudinal distance ($\tilde{y}$) from mouth (m)	Lateral distance (*x*) from *y*-axis (m)
Breathing and talking	1.5	0.88	0.87	0.15
	2.0	1.18	1.17	0.19
	2.5	1.47	1.46	0.24
	3.0	1.77	1.75	0.28
	3.5	2.06	2.04	0.32
	4.0	2.35	2.33	0.36
	4.5	2.65	2.62	0.41
Sneezing and coughing	5.0	2.94	2.91	0.45

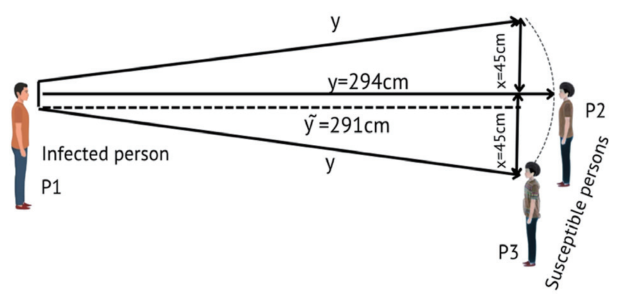


Fig. 6. Suitable social distancing for sneezing and coughing in jet flow (*y*) and lateral (*x*) horizontal directions.

Actually, the vapor concentration in a droplet cloud is typically higher than that of the surrounding environment. This situation can reduce the evaporation rate in the cloud and increase the evaporation time of a single droplet. This may also explain why different researchers found shorter evaporation times compared with the results of the present study.

The intersection point of the curves of falling and evaporation times of respiratory droplets was between 20 and 25 µm in droplet diameter. It can be seen from Fig. 5 that the evaporation lasts for about 125 seconds of a small droplet with 22.5 µm in diameter. A droplet with a diameter of ≤ 22.5 µm could evaporate within the settling time, and its nuclei along with a pathogen, in case there is any, would be suspended in the air for an extended period. On the contrary, the larger droplets (> 22.5 µm) do not remain suspended. These outputs are in agreement with the conclusion of Wang et al.[6] indicating that the droplets with a diameter of 10-40 µm evaporate rapidly. According to Shadloo-Jahromi et al.[38] the droplets smaller than 10 µm can cohere with each other, and this phenomenon may lead to a faster settling. On the other hand, the small droplets are capable of complete evaporation, and the droplet nuclei can remain suspended in the air.[9]

The downward velocity (terminal speed, to be more precise) of a single *Influenza* virus through the air is negligible (5.72×10^{-7} m/s) based on Stokes's law (Table 1). Using Eq. (11), it was estimated that a single virus could float in calm air for 34.4 days when it is released from a height of 1.7 m. This suggests that gravity has a negligible effect on the descent of a virus. In contrast, an isolated *Streptococcus* bacterium can remain suspended in the air for 18.6 hours, with a settling velocity of 2.54×10^{-5} m/s. However, these estimated durations should not be interpreted as indicators of the pathogens' survival time in the air. The longevity of pathogens under moderate conditions of the air can easily be seen in Table 1. On the other hand, the interaction between the pathogen and the droplet should be considered. For example, the droplet with a diameter of 1 µm evaporates completely within a short time (5.56 s) during its fall.

Fig. 6 visualizes droplet transport in the lateral (*x*) and jet flow (*y*) directions. The initial velocity (v_o) of the droplet has great changes in both horizontal transport distances. We distribute the initial velocity (v_o) uniformly in the *x*-*y* plane, where $v_z = 0$. When v_o increases, the quantities of (*y*) and (*x*) are enhanced as can be observed from Fig. 6. In other words, high v_o results in higher transport distance (see Table 2). Assuming a minimum initial velocity of 1.5 m/s for droplets produced by breathing and talking, and 5.0 m/s for those expelled during sneezing and coughing, the horizontal distance traveled by the particle from a height of 1.7 m was calculated to be 0.88 m and 2.94 m, respectively, using Eq. (4). These lower and upper limits for initial velocity were recommended by Aydin et al.[20] However, they restricted their outputs to those situations and ignored the intermediate range of initial velocity and/or different cases. While the geometry used is based on simplified representations of a real system, it seems to be relevant for analyzing the trajectory of respiratory droplets.

Public health practitioners are interested in knowing how far the respiratory droplets containing pathogens can travel in high-risk areas or confined spaces, once the particles leave the source. It mainly depends on the nature of the phenomenon (breathing/talking or sneezing/coughing), droplet diameter, and environmental conditions. The particle sizes are also dependent on the respiratory phenomena. For example, it has been reported that sneezing/coughing produces larger droplets than breathing/talking. At the same time, sneezing/coughing may generate respiratory particles in a wide range (from 1 to 1000 μm, rarely reaching 2000 μm).[7] As reported before, based on Newtonian physics, the equation of free fall [Eq. (4)] is a useful tool to roughly compute the travel distance of large particles from the emitter in the jet flow-horizontal direction when initial position and exit velocity are known and/or assumed. Our results show that the droplets can travel for several meters before reaching the floor, creating a risk of infecting other people in crowded environments (Table 2). On the other hand, a respiratory particle in free fall from a height of 1.7 m can fall to the ground in 0.59 s. Likewise, for droplets with a diameter of 310 μm, the time to reach the ground from the same height is 0.60 s according to the estimates of Stokes's law (data not shown in the results section). These falling durations are comparable with settling time of droplets larger than 800 μm (see Fig. 4) based on the ART model. This means that the large droplets would follow a ballistic trajectory and fall onto surface within seconds. In all cases considered, the free fall approximation may not be accurate for small droplets since the drag force is ignored. Although not all droplets would reach the estimated distances but part of them could. Nevertheless, the estimates of transport distance of expiratory particles in the jet flow direction are in agreement with relevant data reported in the literature to secure a safe social distancing. Despite this fact, the main purpose of this study was not to analyze the validity range of the free fall equation. The primary concern in this study is to obtain the variables/parameters required for Eq. (9) in a convenient way for improving disease transmission prevention, although Eq. (4) has some shortcomings. In this regard, the free fall model is still an appropriate and practical tool as the simplest choice for estimating respiratory particle trajectory in high-risk environments such as healthcare/emergency rooms, even though its estimates are relevant for the motion dynamics beyond an apparent diameter range of micro-scale particles. Usually, a model of motion dynamics considering friction effects in viscous air, such as Stokes's law, is necessary to ascertain the downward velocity of small particles. However, in realistic situations, settling durations predicted by Stokes's equation (for typical diameters ≤ 50 μm) would yield irrational results in terms of horizontal transport distances of respiratory particles, because smaller droplets are extensively subjected to diffusion as time progresses. In addition, the droplet nuclei with a pathogen, if there is any, could remain in the air as an aerosol for a quite long time.

Consequently, the recommended social distancing between the individuals is 2.94 m in jet flow direction (distance y between persons P1 and P2 in Fig. 6) or 2.91 m and 0.45 m in longitudinal and lateral directions (distances $\tilde{y}$ and x between P1 and P3), respectively, for sneezing and/or coughing. In this context, based on the locations of P1 and P3, the distance between infected and healthy persons should be 0.87 m and 0.15 m in longitudinal and lateral directions, respectively, for breathing/talking (Table 2 and Fig. 6). The calculated transport distances of this study are consistent with previous literature data on average.[6, 13, 14, 36] More importantly, the flow pattern in the two horizontal directions (y-x plane) obtained by us is similar to the figure shape shown by Wang et al.[14]

As a matter of fact, the additional spread of droplets due to various factors other than the sneeze/cough-jet was excluded from consideration for simplification in this study. At least, we can discuss the potential extent to which diffusion and other factors affect the lateral spread of droplets remaining airborne over a long time period. The effects of some complex factors -such as airflow (turbulence), diffusion, and ventilation- need to be discussed. Even under the conditions of calm air, there is always some degree of turbulence due to different reasons. In this case, smaller droplets show Brownian motion and follow the convection pattern of the air which would change the spread distance of respiratory particles over time in all directions. Similarly, the particles with intermediate diameters may initially travel ballistically and then diffusively after a short time. In other words, small particles would float in the air and spread much further by the airflow. This means that the diffusion would be a primary mechanism of the spread of small droplets. However, it is difficult to fully assess the effects of all mechanisms on the spread of respiratory droplets within the framework of a single study. In this subject, a well-executed study has been performed by Lee et al.[39] Based on their outputs, small droplets with diameters up to 60 µm tended to disperse more extensively. However, larger particles were less subject to diffusion, although the size of droplets would vary due to their evaporation and/or coalescence. On the other hand, the diffusion of respiratory particles can be significantly controlled by airflow management through an effective ventilation system. Alternatively, other measures (such as personal protective equipment, patient isolation, sealing the front space, etc.) may be necessary to prevent the spread of airborne diseases in high patient-traffic areas like emergency department settings.

According to Sarhan et al.[22] most respiratory droplets fall to the ground due to gravity before traveling 1.5 m in an indoor space. In addition, it is evident that a shorter distance can be sufficient to protect susceptible individuals from droplets emitted by an infected person when face masks are worn. The outputs of this study demonstrate the difficulty of maintaining proper and safe social distances to mitigate disease transmission among the individuals due to crowded (or lack of) space in the hospital emergency departments. In addition, patients positioned laterally (side-lying) on stretchers may increase the risk of direct transmission to those on nearby stretchers, when they cough or sneeze. These risks have also been emphasized by other emergency medicine specialists.[40] The outcomes of this study can enhance the current understanding of respiratory droplet trajectories, thereby improving measures to mitigate transmission.

Obviously, the oversights of this study are related to the neglected convective airflow inhaled by healthy people, aerosols-borne routes, turbulence, Brownian motion, and the collective as well as notable influence of the typical cloud of droplets.[9, 36, 41] To understand the transport dynamics and trajectory of respiratory particles in a droplet cloud or in the form of a single particle, both experimental and theoretical studies are needed. Model results always contain uncertainties. However, they can easily give an idea about the subject under investigation.[23] Therefore, future research should aim at experimental studies to sufficiently verify the presented model.

In conclusion, the model suggested in this study is simple and useful but limited, as it is based on several simplifications. The persons directly facing the infected individual may have a higher risk of the infection through direct contamination than the person standing next to him/her. To decrease the spread of viral and bacterial diseases in gathering places of the emergency departments, the proper social distancing between infected and healthy persons should be about 2.9 m and 0.9 m longitudinally, and 0.45 m and 0.15 m laterally for sneezing/coughing and breathing/talking, respectively. The large droplets with the same diameter led to the same falling time regardless of viral or bacterial load. This research establishes a scientific basis, and the proposed approach would stimulate how to effectively safeguard susceptible individuals from the droplets of infected persons. Future studies should consider throat-mouth-nose geometry in addition to the environmental conditions.

AUTHOR CONTRIBUTIONS

All authors contributed to the conception and design of the study. Numerical calculations and data interpretations were performed by IEA. Illustrations of geometrical shapes and virtual persons were made by BA and SAS. The original draft of the manuscript was written by MA. All authors reviewed and approved the final manuscript.

AVAILABILITY OF DATA AND MATERIAL

Raw data will be made available on request to the corresponding author.

The authors declare no conflict of interest.

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