A-025

Modeling COVID-19 Viral Concentration During Human Movement In Indoor Environment

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Abstract Human expiratory activities periodically generate virus-laden droplets that play an important role in the rapid SARS-CoV-2 infection. Droplets can stay as aerosols in the air with a gradually declining viral load for a long time and can carry the pathogens over a significantly long distance, leading to the always-changing concentration in different spaces. In this work, all contributed particles at the same location with varying origins are integrated to precisely present the dynamic viral concentrations in each part of the overall indoor environment over time.

1. Introduction

The worldwide COVID-19 pandemic has brought many changes in our daily lives and punched a devastating blow to the global economy. It is widely recognized that the higher viral load of the SARS-CoV-2 virus in the upper respiratory tract and the expelling of virus-laden droplets during normal activities, such as talking and breathing, are the primary factors contributing to the rapid growth of COVID-19 infection [1]. Some dangerous variants, e.g., delta variant, and omicron variants, have increased transmissibility, which further brings the world more severe challenges. Mitigation of coronavirus transmission is essential in reducing the risk of COVID-19 infection.

During the virus outbreak, many people are infected due to exposure to the virus in environments. The airborne transmission of aerosols was extensively identified as one of the most dominating ways of getting infected. Hence, the dispersion and residence time of viral aerosols is of utmost interest on virus concentration estimation, especially in indoor environments. Moreover, it is believed that airborne transmission is likely to have been the driving force behind the superspreading that extensively occurred in indoor environments [2]. The aerosol particles in the exhalation air by an infected person during expiratory activities may carry airborne pathogens, which may cause infection if inhaled by others. The number and size of particles in the exhaled breath depend largely on a variety of factors and physical mechanisms, including the location of origin and opening of small airways in the respiratory system [3]. Many studies have investigated the particle size distribution of healthy and infected subjects in breathing, talking, coughing and sneezing [3, 4]. Large droplets follow a ballistic trajectory and tend to settle down under the influence of gravity and evaporate into small nuclei. Small droplets are subject to the ambient airflow and remain suspended in the air for a long time and travel for a farther distance. Besides, the evaporation apparently assists the small particles spread much farther, broadening the coverage. The dispersion and accumulation of aerosol particles in indoor environments are experimentally investigated in the context of the guidelines proposed by national health agencies to control the transmission of COVID-19 [5]. Talib Dbouk and Dimitris Drikakis employ computational multiphase fluid dynamics and heat transfer to investigate the transport, dispersion, and evaporation of saliva particles arising from a human cough [6]. The model of droplet dispersion from coughing is also established to evaluate the transmission risk related to SARS-CoV-2 in [7]. Moreover, the distribution and transmission of virus-laden droplets exhaled in the classroom, conference room and elevator are extensively researched [8-10].

Despite the presence of the viral particle in air samples, the airborne viability of COVID-19 in the aerosols is the utter part, and the viral infectivity is a critical determinant for airborne transmission evaluation. The viable SARS-CoV-2 is detected in some aerosol samples using the cell culture method and isolated in a car driven by a patient [2]. Virus-laden aerosols generated in laboratory conditions are typically infectious for hours after they are emitted. The stability of SARS-CoV-2 in aerosols is evaluated by van Doremalen et al. to achieve a viral half-life of 1.1 h in infectivity, which is nearly 3 h for different humidity conditions measured by Smither et al. [11, 12]. Additionally, the infectivity and virion integrity would be maintained for up to 16 h in aerosol [13]. The infectivity of viral load exhaled by the infector is represented by quanta concentration and quantitatively measured in [14] with viral inactivation rate and environmental factors considered.

Virus-containing droplets are continuously exhaled in various locations at different times during human movement. The ceaseless transmission of contagious particles over time brings about constant changes in the viral load itself and inactivation and virus concentration in various areas. Besides, virus-laden droplets expelled by infected people at a different location would meet somewhere at some time and contribute to the calculation of virus concentration within a control volume. The qualitatively location-specific assessment of viral concentration is proposed with the dual use of computational fluid dynamic simulations and surrogate aerosol measurements for different real-world settings [15]. Not only does the transmission of the virus brings about changes in viral quanta concentration of specific location in overall space, but also the mobility of people. Zhaobin Li et al. analyze the dispersion of cough-generated droplets in the wake of a walking person [16]. To quantitatively and precisely present the virus concentration in each part of the overall indoor environment over time, an approach is proposed in which all contributed viral particles at the same location with various origins and infectivity are integrated. It can quantitatively and accurately measure the virus concentration in an indoor environment with the time and distance of airborne transmission considered, connecting the respiratory droplet physics with the evolution of viral infectivity. Based on human movement trajectory, the location and time of expelled virus droplets can be well achieved to explicitly measure the concentration at any time in a different spot.

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2. Airborne Transmission & Quanta Concentration

2.1 Airborne Transmission

COVID-19 contained in the expiratory droplets expelled from the infector is transported and dispersed in the ambient airflow before finally removed, inactivated, and being inhaled by a susceptible. There are a number of factors that contribute to the movement, horizontally emitted velocity of a droplet, particle's weight and the external environmental. Occasionally coughing and sneezing generate more particles with a higher initial velocity (11.7 m/s for coughing) and virus quanta concentration, while constantly performed breathing and speaking (3.9 m/s for speaking) produce less particles with a relatively lower initial velocity and virus quanta concentration [2]. Large droplets usually settle quickly in a few seconds or minutes and evaporate into small nuclei, where the particle can disperse to a long distance in the vaporization process. Tiny particles, including the evaporated and original expelled, are trapped and carried continuously forward within a moist, warm, turbulent cloud of gas with the help of airflow movement [17]. To facilitate the calculation, we assume the movement of all the virus-laden droplets expelled at each moment is independent and divided into two stages, maintaining a uniform motion of initially horizontal velocity (e.g., 3.9 m/s) in the first phase (e.g., 1 second) and then instantaneously and evenly distributed in overall space. Moreover, the droplets are well-mixed within the moved space.

2.2 Quanta Concentration

The viral load of virus-containing droplets has been changing after leaving human expiratory tract with the airborne transmission and a combination of environmental factors. In particular, the viral load emitted is expressed in terms of quanta emission rate (ER_q, $quanta \cdot h^{-1}$), in which a quantum is defined as the dose of airborne droplet nuclei that would infect 63% of susceptible persons with exposure [2]. The quanta concentration in an indoor area at time $t, q(t)$ is measured by

$$q(t, ER_q) = N_I \cdot \frac{ER_q}{RR_{iv} \cdot V} + \left(q_0 + N_I \cdot \frac{ER_q}{RR_{iv}}\right) \cdot \frac{e^{-RR_{iv} \cdot t}}{V} \quad (1)$$

where ER_q is the quanta emission rate of infector (measure in $quanta \cdot h^{-1}$), q_0 is a constant declaring the initial number of quanta in the space, V (m^3) is the target indoor volume, N_I represent the number of infected individuals in investigated volume, RR_{iv} (h^{-1}) is the removal rate for infectious virus in the considered spaces [14]. RR_{iv} consists of three contributions, the air exchange rate (AER) via ventilation, the deposition on surfaces rate (k) caused by gravitational sedimentation and turbulent eddy impaction and the viral inactivation rate (λ). The typical k is 0.24 h^{-1} and inactivation rate λ of viable COVID-19 particles at typical indoor environment without sunlight is generally 0.63 (h^{-1}) indicated in [2, 14].

The ER_q is determined by viral load in sputum, the volume of signal droplets and the quantity of all expelled droplets per exhalation. Thus, the quanta concentration ER_q is modelled as

$$ER_q = c_v \cdot c_i \cdot IR \cdot \int N_d(D) \cdot dV_d(D) \quad (2)$$

where c_v represent the viral load in the sputum of infector (RNA copies mL^{-1}), IR is the inhalation/exhalation rate produced by the breathing rate and tidal volume, N_d is the droplets concentration of infected person in different expiratory activities ($particles \cdot cm^{-3}$), V_d is the volume of a single droplet with a function of particles diameter D (cm^3) and c_i is the conversion factors present the ratio between one infectious quantum and the infectious dose expressed in viral RNA copies. There is a wide range of variations in the quanta emission estimation via equation (2), depending on these and other factors such as virus concentration in the mouth, activity level, and expiratory activity. With light exercise and speaking, a quanta concentration of 142 ($quanta \cdot h^{-1}$) can be obtained, which was widely adopted in many works [2].

3. Methodology

3.1 Location-Specific Quanta Concentration

Exhalation and inhalation respiratory activities are constantly alternating (e.g., each breath consists of 2.5 seconds of continuous exhalation and 2.5 seconds of continuous inhalation), and droplets are continuously being released from the respiratory tract with a horizontal velocity during the process of exhalation with the same direction as the movement of human. *The movement trajectory of human/virus-laden droplets is presented as a set of points, including time and position,* $\{(t_0, x_0, y_0), (t_1, x_1, y_1), \ldots (t_n, x_n, y_n)\}$ *where* (x_i, y_i) *is the location coordinate and* t_i *is the moment when the individual or the foremost particles reaches the location.* The particles exhaled at each moment will continue to move forward, starting from the user's position when they are expelled. The viral droplets exhaled from the infectious host are transported and dispersed in the ambient airflow before finally being inhaled by a susceptible person. Since each exhalation lasts several seconds (e.g., 2.5 seconds) in which a long distance can be travelled for those who are in motion, and the initial position of droplets expelled cannot be accurately estimated in an indoor environment. Therefore, one complete exhalation period is divided into many short-term (e.g., 0.1 second) particle ejections. Because the interval is short, the *continuous virus exhalation process can be converted into an instantaneous process, namely, the virus is released instantly at the beginning of each interval. The virus-laden droplets expelled at different intervals maintain independent and identical motion pattern* and the initial position of the particles released in each interval can be regarded as the location of the people at its initial moment. *The virus-containing particles maintain a uniform motion of initially horizontal velocity (e.g.,* 3.9 m/s *) in the first second and then instantaneously will-mixed in overall considered space. Meanwhile, the droplets are evenly distributed within the moved space*. In the first movement phase of exhaled droplets in each interval, the virus moves in the same direction as people travel, which is called the forward transmission. As for the backward transmission, in general, the initial velocity of the virus is faster than the speed of people's movement and the speed of airflow, so in the first phase, very few virus particles move at the opposite direction.

Virus-laden droplets exhaled by infectious people at different locations will meet somewhere at some time and contribute to the calculation of concentration during the movement. To precisely present the virus quanta concentration, the transmission of all

virus particles per exhalation source from different origins and in different states is assumed to follow the same pattern, in which the particles keep a constant initial velocity during the first second and then instantly well mixed in the overall space. *The time it takes for the virus to move to the current point and the contribution to virus quanta in the present are estimated with the help of spatial distance and velocity.* Thus, the quanta concentration in a specific indoor area at time $t, q(t, ER_q)$ is measured by

$$q(t, ER_q) = \sum_{i}^{i=N_v} \left(\frac{ER_q^i}{RR_{iv} \cdot V(t^i)} \cdot \left(1 + \frac{e^{-RR_{iv} \cdot t^i}}{V(t^i)} \right) + \left(q_0 \frac{e^{-RR_{iv} \cdot T}}{V} + q_0^i \cdot \frac{e^{-RR_{iv} \cdot t^i}}{V} \right) \right) \quad (3)$$

where RR_{iv} is the virus removal rate of target space, N_v represent the virus generated in different places at different moments, ER_q^i is the of the quanta emission rate of infector at which the virus (i-th) expelled, T is the time difference from the start of experiment to the present, t^i is the time difference between current time and the originating time of virus (i-th), $V(t^i)$ is the volume of the space that the i-th virus has passed since it was expelled to the present, q_0 is the number of environmental virus quanta, q_0^i is the virus exhaled by infector that has already evenly spread to the over investigated space, and V is the overall volume of considered indoor environment. Exhaled virus particles eventually become the environmentally well-mixed virus quanta, while different initial states induce a different decay.

3.2 Quanta Concentration During Human Movement

The algorithm of quanta concentration during human movement in indoor environment is precisely presented in Algorithm 1.

Algorithm 1: Quanta concentration during human movement

Input: Trajectories $Trajs$ of infectors,
target time $\mathcal{T}$
target position $\mathcal{P}$.
Output: virus quanta concentration in $\mathcal{P}$ at $\mathcal{T}$
Initialization: time intervals: Δt,
virus concentration $q_{\mathcal{P}}^{\mathcal{T}} = 0$ in $\mathcal{P}$ at $\mathcal{T}$.
obtain the initial state set $Q = \{Q_0^i\}$ of all viruses expelled at different intervals from $Trajs$, where $Q_0^i = (t_0^i, V_0^i, q_0^i)$
foreach $Q_0^i \in Q$ do
  while $j \leq \lceil \frac{\mathcal{T} - t_0^i}{\Delta t} \rceil$ do
    achieve $Q_j^i = (t_j^i, V_j^i, q_j^i)$ based on movement itself
    if $\mathcal{P}$ *in* V_j^i then
      $q_{\mathcal{P}}^{\mathcal{T}} = q_{\mathcal{P}}^{\mathcal{T}} + q_j^i$
      break
    end
    $j = j + 1$
  end
end
return $q_{\mathcal{P}}^{\mathcal{T}}$

1. Achieve the initial state set $\{Q_0^i\}$ of the expelled particles in each short-term period with the help of human movement trajectories $Trajs$ and the preset particle ejection interval Δt. Q_0^i define the state of all i-th emitted particles in interval Δt and consists of three parts t, V, q where t represents the elapsed time after being exhaled, V represents the spread coverage of droplets due to airborne dispersion, and q represents the quanta concentration.
2. Calculate the state Q_j^i at j-th interval for any Q_0^i after being expelled, combined with the movement pattern of considered particles.
3. Compute the quanta concentration $q_{\mathcal{P}}^{\mathcal{T}}$ in the target position $\mathcal{P}$ at the target time $\mathcal{T}$. The quanta concentration presented within $\mathcal{P}$ at $\mathcal{T}$ by particles expelled in the various intervals is summed to estimate $q_{\mathcal{P}}^{\mathcal{T}}$. Moreover, the quanta concentration presented in different locations at various times can be further evaluated.

4. Evaluation

4.1 Experimental Scenario

We choose the corridor with more movement involved as the experimental scene (which can be easily extended to the room environment with less movement of people) and assume that there is no exchange of viral particles with the room space. Fig. 1 shows the corridor diagram of the experimental scene based on a real environment where the corridor is represented by solid lines and the characters denote the corner point. Based on the practical scenario, the Manhattan distance is applied to measure the distance of virus moved. Since the weight and height of the hallway are generally the same, the volume of the current coverage can be determined by virus movement distance for the calculation of quanta concentration. When the virus encounters a corner, its direction changes, leading to a shift in quanta concentration to varying degrees. For a corner with two branches, the concentration is assumed to decrease by half due to the inertia effect while these viral particles continue the forward transmission. If it is a corner with three or more branches, we assume that the virus quanta will be distributed evenly in all other directions.

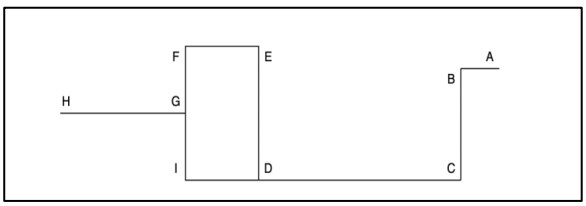

Fig. 1 Digram of experimental scene

4.2 Results

The virus-laden particles released in each interval follow the same movement pattern, leading to the same trend in the change of quanta concentration. We chose the instantaneous concentration at the end of each shorter interval with a length of

0.1 seconds to represent the concentration at all times during the entire interval, as presented in Fig. 2. As can be seen from Fig. 2, the overall change in concentration presents an exponentially decreasing trend, from above 88 in the first interval (0~0.1 second) to close to zero one second later. The sharp decrease one second later is because of an instantaneous expansion of the viral aerosol coverage to the entirely considered space.

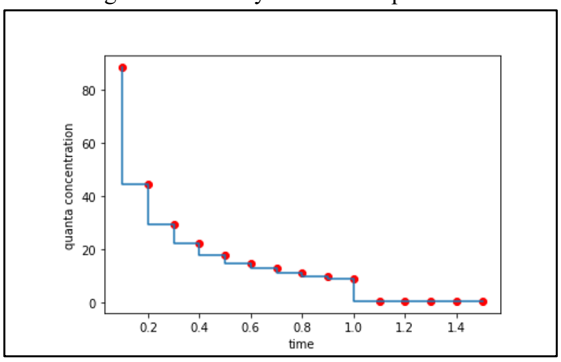

Fig. 2 Quanta concentration of viral particles changes over time (first 1.5 seconds) after being released

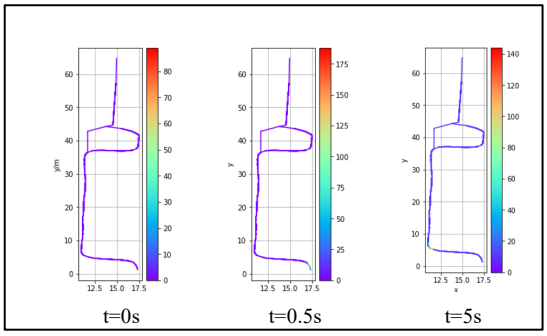

Fig. 3 Quanta concentration at different time

We evaluate the quanta concentration changes over time in the indoor environment with human movement considered, where the walking trajectory is following A→B→C→D→E→F→G →H. The time when people started moving can be seen at the time 0 of the experiment. We present the quanta concentration in the space at the time of 0s, 0.5s and 5s, which are shown in Fig. 3 (The reason for the subtle difference between the corridor Fig. 3 and Fig. 1 is that we use the real trajectory of the tester to show the effect of people's movement on quanta concentration in the space). Among them, at t=0s, only the virus concentration near point A can be seen to exceed 88, while most of the other part was not covered by viral particles. At t=0.5s, under the combined movement of virus droplets and humans, the relatively high virus concentration covered more. In addition, after another 0.5 seconds, the particles initially expelled at t=0s will spread to the overall space. At t=5s, the area with higher quanta concentration gradually moves forward with the movement of people. Moreover, due to the accumulated particles that diffused into the entire environment, the quanta concentration in overall space is increased.

5. Conclusion

Over the course of this pandemic, the transmission of the virus has been extensively studied to relieve the situation. We establish a model to evaluate viral quanta concentrations expelled because of human movement and the airborne dispersion of virus particles. The proposed model exploits the transmission and attenuation of viruses in the air and the trajectories of people with virus-laden droplets exhaled to estimate the quanta concentration in an indoor environment at different times for prevention and sanitization. In future work, we will consider combining contact detection and tracing with the model to effectively mitigate the pandemic.

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