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Size dependent infectivity of SARS-CoV-2 via respiratory droplets spread through central ventilation systems

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ABSTRACT

Here we evaluate the transport of respiratory droplets that carry SARS-CoV-2 through central air handling systems in multiroom buildings. Respiratory droplet size modes arise from the bronchioles representing the lungs and lower respiratory tract, the larynx representing the upper respiratory tract including vocal cords, or the oral cavity. The size distribution of each mode remains largely conserved, although the magnitude of each droplet mode changes as infected individuals breathe, speak, sing, laugh, cough, and sneeze. Here we evaluate how each type of respiratory droplet transits through central ventilation systems and the implications thereof for infectivity of COVID-19. We find that while larger oral droplets can transmit through the air handling systems, their size and concentration are greatly reduced with but few oral droplets leaving the source room. In contrast, the smaller droplets that originate from the bronchioles and larynx are much more effective in transiting through the air handling system into connected rooms. This suggests that the ratio of lower respiratory or deep lung infections may increase relative to upper respiratory infections in rooms connected by central air handling systems. Also, increasing the temperature and humidity in the range considered after the droplets have achieved an “equilibrium” size reduces the probability of infection.

1. Introduction

Since the first modern air conditioner was invented in 1902 [1], human activities rely increasingly on climate-controlled indoor environments. Yet, most super-spreader events of the COVID-19 pandemic have been recorded within the indoor environment. Professional engineering societies that design heating, ventilating, and air-conditioning (HVAC) systems rely on the steady-state Wells-Riley equation for a single room as a simple model to develop indoor ventilation standards and guidelines [2]. Yet, assuming a single room has led to some recommendations that are not practical to implement at the whole building scale. For example, some have recommended increasing outdoor air to 100% (assuming outdoor air is virus free), even though most HVAC systems are not capable of supplying 100% outdoor air because HVAC systems are designed and sized to balance requirements for thermal comfort, acceptable indoor air quality, and energy use. (Most commercial buildings including skyscrapers have moved away from the use of operable windows, rendering natural ventilation techniques useless.) Furthermore, taking in 100% outdoor air means exhausting a corresponding amount of the indoor air to effectively balance building pressure requirements, and most buildings do not filter respiratory droplets but exhaust them directly outside presenting an unquantified risk to the surrounding population. Ventilation standards (e.g., air change rates) have remained almost unchanged in the past century. It is time to re-evaluate how mechanical ventilation is used to reduce viral loading and minimize disease transmission coherent with accumulated knowledge in virus transmission.

Key among knowledge developed over the past decades is that...
enveloped viruses (e.g., SARS-CoV-2, influenza) transmit within respiratory droplets. Unlike nonenveloped viruses (e.g., polio) that can be infectious outside of respiratory droplets, enveloped viruses themselves must remain hydrated in the environment to be fully infectious. Therefore, reducing the spread of respiratory droplets is essential to slowing the spread of respiratory viruses including but not limited to SARS-CoV-2. The extent of each type of respiratory droplet release varies with, at least, index patient behavior (coughing, sneezing, singing, laughing, talking, breathing, and the vigor of such), the viral loading of the droplets, and the natural history of the disease (a term of art in medicine). However, the droplet size distributions from the respiratory/ oral tract are approximately invariant even if their absolute/relative magnitudes and viral loading vary. Therefore, while we cannot predict the next respiratory illness that buildings will be asked to ameliorate, we can evaluate the spread of different types of droplets so that when the next disease does arrive, we will be better prepared.

Respiratory droplets have a distinctive set of modes in their size distributions, which has not always been recognized in transport and fate analyses. Yang and Marr [3] evaluated the removal efficiencies and droplet size distributions in a single room for influenza A but did not include multiroom effects and only looked at the largest droplet sizes based on the seminal work of Duguid [4] in 1946, which misses the smaller sizes that may transit air handling systems more readily. Indeed, Morawska [5] reviews size distributions from various sources and asserts that early investigators only looked at the “super-micrometer size”. Johnson, et al., [6] evaluated the modality of size distributions of human expired aerosols. They divided the size distribution into three modes labeled the (B) bronchiolar fluid film burst mode, the (L) laryngeal mode, and the (O) oral mode, and give the B mode as centered at 1.6 μm, the L mode as centered at 1.7–2.5 μm, and the O mode as centered at 123–145 μm. Each mode has a broad distribution and assumptions made during analysis may shift these modes by a factor of two. Asadi, et al., [7] showed that different types of speech produce different amounts of respiratory droplets with substantially more droplets from louder speech. The droplets are typically on the order of a micrometer, consistent with the L mode.Gregson, et al., [8] found quiet singing, speaking and breathing to be statistically similar to each other but at the loudest volumes substantially more aerosol mass is focused on sizes <20 μm. Fennelly [9] reviews bioaerosols and asserts that droplets <5 μm deposit in the lower human respiratory tract (bronchi 2.1–3.3 mm; alveoli 0.65–1.1 μm) but larger particles 6–12 μm deposit in the upper airways. In contrast to the assertion of Johnson, et al., [6], Fennelly [9] asserts that some viruses concentrate more in breath (i.e., B and L modes) than in cough (i.e., O mode) including human rhinovirus. Indeed, they report more viral RNA is found in smaller particles than larger, but whether this translates into intact infectious virus concentrations remains unclear.

Pease, et al., [10] evaluated the multiroom spread of SARS-CoV-2 containing respiratory droplets but did not tie their analysis to the droplets distributions as they are emitted from the various parts of human airways. Their analysis leads to several important questions, two of which will be addressed here: What droplet sizes survive through ventilation systems to connected rooms? How do room air temperature and relative humidity (RH) affect the probability of infection after the droplets have been formed?

In this article, we consider the three droplet modes and explore their transport and fate through a typical central air handling system. We evaluate the influence of filtration, air changes per hour (ACH), and outdoor air intake on the modes. We use droplet size specific models to estimate the probability of infection for both transient and steady-state exposures.

2. Materials and methods

Our approach combines the multiroom approach of Pease, et al., [10] with the droplet size specific approach of Yang and Marr [3] starting with the multimodal droplet size distributions of Johnson, et al., [6]. We also evaluate the infectivity model of Buonanno, et al., [11] to account for the influence of respiratory droplet sizes. We use the term droplet here to represent aerosolized materials that start as a droplet regardless of whether they remain as a liquid droplet, dry to a solid material, or are a combination thereof.

Pease, et al., [10] give our multiroom model as

\[
\begin{align*}
\frac{dC_{\text{source}}}{dt} &= \lambda C_{\text{post}} + C_{\text{generation}} - \left( \lambda + \frac{V_i}{H_i} + k_{\text{decay}} \right) C_{\text{source}} \\
\frac{dC_{\text{connected}}}{dt} &= \lambda C_{\text{post}} - \left( \lambda + \frac{V_i}{H_i} + k_{\text{decay}} \right) C_{\text{connected}} \\
\frac{dC_{\text{plenum}}}{dt} &= f_p \lambda C_{\text{source}} - \left( f_p + \frac{V_i}{H_i} + k_{\text{decay}} \right) C_{\text{plenum}} \\
\frac{dC_{\text{post}}}{dt} &= \lambda_{\text{pre}} C_{\text{plenum}} - \left( 1 + f_\lambda \lambda_{\text{pre}} + \frac{V_i}{H_i} + k_{\text{decay}} \right) C_{\text{pre}} \\
\frac{dC_{\text{post}}}{dt} &= (1 - \epsilon) \lambda_{\text{post}} C_{\text{pre}} - \left( \lambda_{\text{post}} + \frac{V_i}{H_i} + k_{\text{decay}} \right) C_{\text{post}}
\end{align*}
\]

(1)

where C is the concentration of droplets (with subscript indicating the source room, the connected room, the common overhead plenum, and the portions of the air handling unit (AHU) pre-filter and post-filter), λ is the air changes per hour (with subscripts p, pre, and post to indicate the plenum and pre-filter and post-filter portions of the AHU, respectively), ε is the efficiency of the filter in the AHU, νℓ is the settling velocity, H is the height of the volume of interest (i.e., the physical volume of a room divided by its square footage, each with their corresponding subscript), kdecay is the decay constant, f_p is the fraction of the volumetric flowrate entering the plenum from the source room, and f_λ is the fraction of outdoor air. In the interest of brevity, the reader is referred to Pease, et al., [10] for a complete derivation. Although the units of Eq. 1 are quite general, here we select concentration with units of number per volume or quanta per volume. At time zero, all concentrations are zero, and concentration is driven by the generation term in the first of this set and is addressed subsequently in Eq. 5. For completion, these equations require a settling velocity given by

\[
\nu_ℓ = \frac{\rho_f - \rho_i}{18 \mu_f} \left( \frac{g \rho_f}{\rho_i} \right)^{1/2}
\]

(2)

to first order approximation, where \(\rho_f\) is the density of the droplet, \(\rho_i\) is the density of the fluid, \(g\) is the gravitation constant, \(\mu_f\) is the diameter of the droplet, and \(\mu_f\) is the dynamic viscosity of the fluid. These equations were solved in Mathematica (Wolfram Research, Champaign, IL). Because filtration is important as a function of size, distributions were fit using sigmoidal curves (compare [12]) to evaluate particle penetration and removal efficiencies (see Fig. 1). Viral degradation is given by

\[
k_{\text{decay}} = \begin{cases} 
0.1603 + 0.04018 \frac{T - 20.6515 \degree C}{10.585 \degree C} + 0.02176 \frac{RH - 45.235}{28.665} \\
+ 0.14369 \frac{S - 0.95 W/m^2}{0.95 W/m^2} + 0.02636 \frac{T - 20.6515 \degree C - 0.95 W/m^2}{10.585 \degree C - 0.95 W/m^2} & \text{60 hours} 
\end{cases}
\]

(3)

with temperature \(T\) in \(\degree C\), relative humidity \(RH\) in percent and UV radiation \(S\) in \(W/m^2\) [13,14]. Negative values from this formula are treated as 0/h. Parameters used in these simulations are given in Table 1. The driving force in Eq.1 is the generation term in the source room, which is related to the droplet size distribution. Following Buonanno, et al., [11] the infectious dose in quanta per hour from a virus shedder may be estimated as the product of the exhaled gas volume per time, the number of droplets per that volume, the liquid volume per droplet, the number of RNA copies per liquid volume, and the number of quanta per RNA copy, given here as
Fig. 1. Size specific information including filter removal efficiency curves and source initial size distributions. The initial size distributions divided by the rational coefficient in Eq. 9 to enhance visual clarity. Colour coding of droplets online only preserved in subsequent figures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

\[ q = c_j p_{ex} \left( \sum_i c_{vi} \int N_i dV \right) \]  

(4)

where \( c_j \) is a conversion factor between RNA copies and infectious dose, \( p_{ex} \) is the volumetric flowrate of exhaled breath, \( c_{vi} \) is the viral load for each mode \( i \) (i.e., bronchiolar, laryngeal, oral), \( N_i \) is the number of droplet number concentration (e.g., in particles/cm\(^3\)), and \( V \) is the liquid volume per droplet. Masks, where present, fractionally decrease \( q \).

Then at any given moment

\[ \dot{c}_{\text{generation}} \sim \frac{q}{V_{\text{source}}} \]

(5)

where \( V_{\text{source}} \) is the physical volume of the room (square footage multiplied by average height). An expression for \( N_i \) completes the solution for concentration. Johnson, et al., [6] give the size distributions across all three modes as

\[ \frac{dN_{\text{cumulative}}}{d\log d_p} = \ln 10 \sum_i A_i \sqrt{2\pi\sigma_i} \exp \left[ -\frac{(\ln d_p - \ln M_i)^2}{2\ln^2 \sigma_i} \right] \]

(6)

where \( A_i, \sigma_i, M_i \) are constants corresponding to each respective BLO mode \( i \) (see Table 2). This formulation inspires our use of the Gaussian distributions in Fig. 1; mode specific coefficients are not used herein so that each mode starts with approximately the same number of droplets (the equations governing concentration are linear). In Eq. 4, \( N_i \) is not the cumulative number of particles but the incremental number of particles corresponding to a differential droplet volume \( dV \). Then the mode specific cumulative distribution of droplets may be evaluated as

\[ N_i = \frac{A_i}{\sqrt{2\pi\sigma_i}} \int \exp \left[ -\frac{(\ln d_p - \ln M_i)^2}{2\ln^2 \sigma_i} \right] d\ln d_p \]

(7)

For each droplet size \( d_p \), the infective dose may be approximated as

\[ \text{Infective Dose} \sim \exp \left( \frac{(\ln d_p - \ln M_i)^2}{2\ln^2 \sigma_i} \right) d\ln d_p \]

Table 1
Simulation parameters.

| Parameter Name                                      | Variable  | Baseline Value | Range Evaluated |
|----------------------------------------------------|-----------|---------------|-----------------|
| Air Change Rate (Source and Connected Rooms)       | \( \dot{h} \) | 6 ACH         | 1.8–12 ACH      |
| Room Height                                        | \( H \)   | 8 ft          |                 |
| Fraction from Source Room to Plenum                | \( f_S \)  | 1/3           |                 |
| Air Change Rate in Plenum                          | \( \dot{z}_p \) | 24 ACH        | 22–144 ACH      |
| Plenum Height                                       | \( H_p \)  | 2 ft          |                 |
| Fraction Outdoor Air                               | \( f_{OA} \) | 9%            | 0.3–33%         |
| Air Change Rate in AHU Before Filter               | \( \dot{z}_{pre} \) | 36.9 ACH | 17–74 ACH       |
| Air Change Rate in AHU After Filter                | \( \dot{z}_{post} \) | 61.4 ACH | 18–123 ACH      |
| AHU Height                                          | \( H_{pre} = H_{post} \) | 2 ft  |                 |
| Release Time1                                       | \( \Delta t \) | 5 min; continuous | 0–2.08/h     |
| Virus Decay Rate2                                   | \( k_{decay} \) | 0.088/min = 0.48/h | 0–2.08/h |
| Physical Volume of Source Room                     | \( V_{\text{source}} \) | 512 ft\(^3\) |                 |
| Physical Volume of Connected Room                  | \( V_{\text{connected}} \) | 512 ft\(^3\) |                 |
| Physical Volume of Overhead Plenum                 | \( V_{\text{plenum}} \) | 128 ft\(^3\) |                 |
| Physical Volume of AHU Before Filter               | \( V_{\text{pre}} \) | 250 ft\(^3\) |                 |
| Physical Volume of AHU After Filter                | \( V_{\text{post}} \) | 150 ft\(^3\) |                 |
| Number of Connected Rooms                          | \( N_{\text{rooms}} \) | 2             |                 |
| Droplet Density                                     | \( \rho_d \) | 998 kg/m\(^3\) | 992–998 kg/m\(^3\) |
| Density of Air                                      | \( \rho \)  | 1.2 kg/m\(^3\) | 1.1–1.2 kg/m\(^3\) |
| Dynamic Viscosity of Air                           | \( \mu \)  | 1.810\(^{-5}\) Pa s | 1.8–1.9 \(10^{-5}\) Pa s |
| Gravitational Constant                             | \( \varepsilon \) | 9.8 m/s\(^2\) |                 |
| Dose Conversion Factor                              | \( c_{j} \) | 0.02 quanta/RNA |                 |
| Breathing Rate1                                     | \( p = p_{ex} \) | 0.48 m\(^3\)/h |                 |
| Viral Load1                                         | \( c_{vi} \) | \( 10^{10} \) RNA copies/mL |                 |

1 Release time corresponds to a duration of release of virus from an infected individual.
2 Ref. [13], corresponds to 10-30 °C, 20–70%, and 1–1.9 W/m\(^2\).
3 Buonanno, et al., [11] use \( c_{j} = 0.01–0.1 \) quanta/RNA copy and prefer 0.02 quanta/RNA copy based on SARS-CoV-1.
4 During resting and standing, Buonanno, et al., [11].
5 Within a typical range of \( 10^5–10^7 \) RNA copies/mL for COVID-19 patients.

Table 2
Parameters used for size distributions modes.

| Mode | \( A_i \) (droplets/cm\(^3\)) | \( M_i \) (\( \mu \)m) | \( \sigma_i \) (\( \mu \)m) |
|------|-------------------------------|-----------------|-----------------|
| Bronchiolar (B)                  | 0.054–0.090                | 1.6             | 1.25–1.30       |
| Laryngeal (L)                    | 0.068–0.14                  | 1.6–2.5         | 1.66–1.68       |
| Oral (O)                         | 0.0013–0.016                | 123–145         | 1.80–1.84       |

1 Selected from Tables 2–4 of Johnson, et al., [6].
\[ q_i = \frac{\pi}{6} \sigma_i^3 \rho \epsilon_i c_i d_i^3 \left( \frac{dN}{dd_i} \right) \Delta d_i \]  
\tag{8}

for each mode, where \( \Delta d_i \) is an increment in particle diameter (here \( \sigma_i/10 \)). The mode specific generation rate in Eq. 1 is that a function of both time and particle diameter is then

\[ \dot{C}_{\text{generation},i} = \sqrt{\frac{\pi}{2}} \rho \epsilon_i c_i A_i \sigma_i d_i^2 \Delta d_i \exp\left[ -\frac{(\ln d_i - \ln M_i)^2}{2 \ln \sigma_i} \right] \times \left( \frac{1}{1 + \exp[-s(t - 0.1\text{min})]} - \frac{1}{1 + \exp[-s(t - \Delta t - 0.1\text{min})]} \right) \]  
\tag{9}

where the final factor governs the timing of the release where \( \Delta t \) is the duration of release and \( s \) governs the slope of each step function (30,000/h), and the leading \( \ln \sigma_i \) requires \( \sigma_i \) in units of microns. When the release is continuous, the final factor resolves to unity. The rational coefficient of the exponential is not used in figures representing concentration to improve figure clarity, but is used in figures representing probability of infection.

The risk of infectivity depends on whether the concentration in the breathing zone is truly spatially uniform or whether the virus concentration has some spatial heterogeneity relative to the spatially averaged concentration. The Wells-Riley approach assumes that the spatial concentration is uniform so that the cumulative probability of infection, \( P \), may be based on the Poisson distribution and given by

\[ P = 1 - e^{-\mu} \]  
\tag{10}

where \( \mu \) is the average number of quanta breathed by a susceptible person, meaning someone who could become infected \([2,10]\). Rudnick and Milton \([15]\) relate the average number of quanta (one quantum gives a 63% probability of inducing infection) breathed to the average quantum concentration, where this average is generalized as

\[ \mu = \rho \sum_i \int_{t_1}^{t_2} C_i dt \]  
\tag{11}

where \( G_i \) is any of the concentrations in any of these rooms specific to mode \( i \) in units of quanta per volume, \( \rho \) is the volumetric inhaled breathing rate, and \( t_1 \) and \( t_2 \) are the starting and ending times of exposure (where \( t_2 > t_1 \geq 0 \)).

\[ P = 1 - \exp\left[ -\frac{\pi}{2} \rho \int_{t_1}^{t_2} C d^2 d \right] \exp\left[ -\frac{\pi}{2} \rho \int_{t_1}^{t_2} C_1 d^2 d \right] \exp\left[ -\frac{\pi}{2} \rho \int_{t_1}^{t_2} C_2 d^2 d \right] \]  
\tag{12}

where the subscript on \( C \) indicates the droplet generation mode. For an individual mode only one exponential is evaluated. The figures below numerically approximate the probability of infection using the mode instead of quadrature. The community’s public health risk may be estimated with a replication number as

\[ R_n = (n - 1)P \]  
\tag{13}

where \( n \) is the number of people in the space (including the one shedding virus).

The fraction of the population that is infectious, \( f_{\text{infectious}} \), at any given time may be estimated via

\[ f_{\text{infectious}} = \frac{N_{\text{new cases}} N_{\text{infectious}}}{N_{\text{population}} \times \text{measured}} \left[ f_{\text{presymptomatic}} + (1 - f_{\text{presymptomatic}}) (1 - f_{\text{isolate}}) \right] \]  
\tag{14}

where \( N_{\text{new cases}} \) is the number of measured new cases per day (~40,000–80,000/day, April-October, 2020 US), \( N_{\text{days infectious}} \) is the number of days that an individual remains infectious (e.g., 12 days), \( N_{\text{population}} \) is the population of interest (e.g., 320,000,000 in the US), \( f_{\text{measured}} \) is the fraction of the cases that are measured (~10% per CDC estimates), \( f_{\text{presymptomatic}} \) is the fraction without symptoms (including asymptomatic and paucysymptomatic, ~10–60% may be presymptomatic [16–18]), \( f_{\text{isolate}} \) is the fraction of individuals who isolate (e.g., ~90% [19]). The fraction of healthy individuals also quarantining could affect these estimates.

3. Results and discussion

The purpose of this article is to evaluate the transport and fate of respiratory droplet modes through central air handling systems. Respiratory droplets come in three modes: the (B) bronchiolar fluid film burst mode (peak ~1.6 \( \mu \)), the (L) laryngeal mode (peak ~1.7–2.5 \( \mu \)), and the (O) oral mode (peak ~123–145 \( \mu \)). This analysis evaluates the fate of these three types of respiratory droplets through centralized air handling systems. Even at the height of most pandemics most people one meets are not infectious. The fraction of the people in public that may be contagious may be estimated via Eq. 14 for SARS-CoV-2 in the US April through October 2020 as ~0.6%. It is to reduce exposure to this small but infectious fraction of the population that interventions including distancing, masks, and ventilation, etc. are designed to protect against. Here, our focus is on how ventilation systems affect viral spread from this group.

The influence of a ventilation system depends on both the duration of viral shedding within a room and mechanisms of viral removal and inactivation. The room in which viral shedding occurs is termed the source room and other rooms connected via the air handling system are termed connected rooms. Fig. 2 shows that as the duration of viral shedding increases, the concentration of infectious respiratory droplets in both the source and connected rooms increases. In the source room, respiratory droplets generated are removed by settling, viral degradation, and removal through the air handling system, though some respiratory droplets may be re-introduced by the air handling system. When the rate of generation is balanced by these removal mechanisms, the concentration of respiratory droplets achieves a steady state. This steady-state concentration is the highest concentration achieved. As the duration of viral shedding decreases (because biological sources cease, personal protective equipment is donned, or the shedding individual leaves the building), the concentration in the source room drops with a time scale set by the viral decay rate, the droplet settling rate, and the ventilation rate. The concentration within the connected room is further attenuated by settling and viral decay within the air handling system including the plenum and ducting, which lower the concentration and extend the concentration decay times within the connected rooms relative to the source room. Subsequent figures evaluate concentration profiles and droplet size distributions at five minutes and the steady-state extrema shown in Fig. 2.

Fig. 3 shows how the droplet size distributions vary as a function of
The droplet distributions as described by Johnson, et al., [6] are approximately log-normal and are for respiratory droplets or dried particles that contain virus and not for naked virus alone. For example, the SARS-CoV-2 virus has a size, inclusive of spike proteins, of 0.05–0.20 μm, which is smaller than the droplets represented in the figure [20]. Each distribution here is normalized to one by integrating over size in standard statistical form. Each of the four panels shows that the size distribution of the bronchiolar mode does not change substantially over time in either the source room or connected rooms as distributions by number or volume. In contrast, the respiratory droplets of the oral mode do change over time substantially in both rooms, shrinking over time. The oral droplets in the connected rooms are smaller than the ones in the source room but appear to approach ~10 μm in diameter over time as presented. The laryngeal droplets do change but only marginally. These droplet sizes are important because the bronchiolar and laryngeal droplets deposit in the lower human respiratory tract (bronchi 2.1–3.3 μm; alveoli 0.65–1.1 μm), in contrast to the larger droplets (6–12 μm) that deposit in the upper airways consistent with those remaining from the oral distribution [9]. Fig. 4 shows that the bronchiolar respiratory droplets do transit through central ventilation systems (in contrast to the oral droplets that do not as shown in the figures below), suggesting that though the risk for an upper respiratory infection may be substantial in the source room, the risk for a lower respiratory infection may dominate the connected rooms and is only partially ameliorated by central ventilation systems.

The size distributions in Fig. 3 are distinct from those of Yang and Marr [3], who use the older Duguid distribution from 1946 that are weighted heavily toward the larger droplets that were readily measurable using historical methods. They find that the droplet size distribution shifts toward smaller sizes over time, similar to our finding for the oral mode. However, they did not resolve the bronchiolar and laryngeal modes, which change much less dramatically. These distributions also
differ from Yang and Marr [3] because they are normalized in a statistical sense permitting the concentration (subsequent figures) and the size distributions (Fig. 3) to be decoupled. Worthy of emphasis is that the droplets themselves are not changing in this analysis—which begins once the droplets have either achieved an equilibrium size or dried out—but the distribution of droplets that persist after various loss mechanisms have taken effect.

Our model permits evaluation of both temperature and humidity via viral degradation rates. These rates are infectious species specific, and Fig. 4 is specific to SARS-CoV-2 [13]. The droplet size distributions do not change meaningfully with changes in either humidity or temperature but overlap trivially on the corresponding curves of Fig. 3 (not shown). This is an important point, because it makes the size distributions of Fig. 3 independent of the species within the respiratory droplets and a surprise because Yang and Marr [3] suggest that the size distributions would depend on humidity (temperature was not part of their analysis). However, the profiles of concentration versus time do vary meaningfully with relative humidity and temperature. Fig. 4 shows that as the relative humidity or the temperature increases, the concentration of infectious respiratory droplets decreases. Because the primary cause of this change is through the viral degradation rate, the concentration of infectious and non-infectious respiratory droplets would not be expected to show a strong temperature or relative humidity effect once the droplets are formed and in the absence of modest droplet size change when the relative humidity increases, as articulated by Yang and Marr [3]. Humidity differentiated probabilities of infection are not well established in the literature and are not addressed herein. Though the temperature range is limited to ≥10 °C in the data of Dabish, et al., [13] on which these curves are based, our finding that lower temperatures increase the concentration of infectious respiratory droplets is consistent with the observation of super-spreader events in cold storage facilities, meat packing plants, and increased viral spread during the colder months of the year. The observation of decreased concentrations of infectious respiratory droplets under increased temperature or relative humidity presents an opportunity to design and operate air handling systems to reduce the load of infectious respiratory droplets, though this article does not address the energy costs or design changes necessary to make such an approach effective.

In the remainder of this analysis, we now consider a continuous viral shedding event (Figs. 5-6) and evaluate its infectious concentration profiles (Fig. 5) and infectious probabilities (Fig. 6) versus time for each of the droplet modes. Corresponding figures for a five-minute viral shedding event are found in Appendix A as Figs. A1-A2. The focus is on temporal profiles because the droplet size distributions for the B and L modes change but modestly in contrast to the concentration profiles that change substantially over time.
Fig. 5. Infectious concentration of respiratory droplets of B (blue), L (red) and O (orange) modes in source room (a,c,e) and connected rooms (b,d,f) versus exposure times at 20 °C and 35% RH for cases in Table 3 with continuous viral shedding in the source room for (a,b) filtration levels of no filtration (short dash), MERV-8 filters (long dash), MERV-11 filters (alternating dash), and MERV-13 filters (solid); for (c,d) 1.8 ACH (short dash), 3 ACH (alternating dash), 6 ACH (long dash), and 12 ACH (solid); for (e,f) outdoor exchange of 0% (short dash), 6% (alternating dash), 9% (long dash), and 33% (solid). The O mode for connected rooms overlaps the abscissa. The initial size distributions divided by the rational coefficient in Eq. 9 to enhance visual clarity consistent with Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Fig. 6. Approximated probability of infection for respiratory droplets of B (blue), L (red) and O (orange) modes in source room (a,c,e) and connected rooms (b,d,f) versus exposure times at 20 °C and 35% RH for cases in Table 3 with continuous viral shedding in the source room for (a,b) filtration levels of no filtration (short dash), MERV-8 filters (long dash), MERV-11 filters (alternating dash), and MERV-13 filters (solid); for (c,d) 1.8 ACH (short dash), 3 ACH (alternating dash), 6 ACH (long dash), and 12 ACH (solid); for (e,f) outdoor exchange of 0% (short dash), 6% (alternating dash), 9% (long dash), and 33% (solid). The O mode for connected rooms overlaps the abscissa. Modes evaluated independently at $M_i$ (B and L modes) or along diameter corresponding to the peak concentration (O mode). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Cases considered [10].

| Number | Case                              | ACH     | Filter    | Outdoor Air |
|--------|-----------------------------------|---------|-----------|-------------|
| 1      | Baseline (code compliant)         | 6       | MERV 8    | 9%          |
| 2      | No filtration                     | 6       | No Filter | 9%          |
| 3      | High filtration                   | 6       | MERV 11   | 9%          |
| 4      | Extra high filtration             | 6       | MERV 13   | 9%          |
| 5      | Extra low air change rate         | 1.8     | MERV 8    | 29%         |
| 6      | Low air change rate               | 3       | MERV 8    | 17%         |
| 7      | High air change rate              | 12      | MERV 8    | 4%          |
| 8      | No outdoor air                    | 6       | MERV 8    | 0%          |
| 9      | Less outdoor air                  | 6       | MERV 8    | 6%          |
| 10     | More outdoor air                  | 6       | MERV 8    | 33%         |

Figure 5 presents concentration profiles corresponding to a continuous viral release event. The panels on the left correspond to the spatially averaged concentration in the source room and the panels on the right correspond to the spatially averaged concentration in the connected room. The starting concentration of each mode in the source room is indicated in Fig. 1. In the source room, the resulting concentrations of the B and L modes are similar. However, the well-mixed concentration of the O mode rises but insignificantly commensurate with this mode’s larger size and corresponding fast settling rate. This suggests that very little of the O mode is available for transit into the connected rooms as seen in Fig. 5. The amount of O that does transit into the connected rooms may be very small and depends at least on the balance between settling rates and local air velocities. This rapid loss of the largest droplet sizes is similar to that observed by Yang and Marr [3] based on the large droplet size distribution of Duguid [4].

Figure 5 also evaluates the cases in Table 3, which span changes in filtration, air change rates, and amount of outdoor air added. Panels a and b show that ideal filtration decreases the concentration of particles in the source room and more dramatically in the connected rooms. These filtration efficiencies are comparable to the filtration efficiencies of Dols, et al., [12] and may differ from commercially available filters. Panels c and d show that increasing the ACH decreases the concentration in the source room. Yet, in contrast to packaged terminal air conditioner (PTAC) systems found in motels, central ventilation systems connect the flow across rooms providing a means of respiratory droplet spread to connected rooms. In the connected rooms, higher ACH translates into faster exposure but also faster removal of respiratory droplets from the connected rooms, which translates into some unexpected and nonlinear infection probabilities. Simply increasing the ACH does not always translate into a lower probability of infection. Although in principle preventing recirculation in buildings may be ideal as a means of preventing respiratory droplet spread into connected rooms, recirculation is “hard wired” into a substantial portion of the world’s building portfolio. Panels e and f highlight the relatively modest influence of outdoor air in both source and connected rooms for the range of variation considered (0–33% outdoor air fraction). These trends with respect to filtration, air change rates, and outdoor air addition are similar to the 5-min shedding event previously described by Pease, et al., [10] albeit not differentiated by respiratory droplet type. In each of these variations, three features stand out. First, the absence of the O mode in each set of curves for the connected room(s) is distinctive. Second, the B and L droplets have similar trends and are close together in each connected room case and even closer in the source room, which is not surprising given their similarity in peak size (1.6 μm versus 2.4 μm). Third, the L mode is always below the B mode because removal by droplet settling rates and filtration efficiencies increase with size in this range (Fig. 1). The finding of significant quantities of B and L droplets in the connected room(s) is important because it indicates that these smaller droplet sizes may be most responsible for spread of infectious particles in respiratory droplets through air handling systems.

For continuous shedding, even though the concentration may plateau, the risk continually increases. Indeed, for most times, the concentration rises linearly after a short induction period. Filtration reduces the risk, increased air flow rates decrease risk in the source room, and more outdoor air is helpful in both rooms. What is unusual with respect to risk is what is happening in the connected rooms as air change rates vary (Fig. 6d) where the curves exchange. Each curve has a different slope and a different induction period so that the scenario which has the highest risk changes with time. Please also note that in all cases because there is linear increase in risk the probabilities of infection can mount quickly and do not plateau like the short-term release cases (see Fig. A2). This leads to substantially higher probabilities than seen for short duration exposures.

In summary, we find that oral droplets responsible for upper respiratory infections generally do not transit central ventilation systems but the smaller bronchiolar and laryngeal droplets do transit between rooms via the air handling system by combining the multiroom approach of Pease, et al., [10] with the multimodal droplet size distributions of Johnson, et al., [6]. Elevating the temperature and humidity within the range considered reduces the infectious concentration of respiratory droplets.

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Declaration of Competing Interest

None.

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Appendix A

For short-term shedding events, filtration, gravitational settling, viral decay, and removal by exchange with outdoor air reduce the concentration down to vanishingly small quantities. This translates to probabilities of infection in contrast to Fig. 6 that plateau over corresponding time scales. Each of these time scales are substantially longer than the 5 min of viral shedding but finite in length.
Fig. A1. Infectious concentration of respiratory droplets of B (blue), L (red) and O (orange) modes in source room (a,c,e) and connected rooms (b,d,f) versus exposure times at 20 °C and 35% RH for cases in Table 3 following 5 min of viral shedding in the source room for (a,b) filtration levels of no filtration (short dash), MERV-8 filters (long dash), MERV-11 filters (alternating dash), and MERV-13 filters (solid); for (c,d) 1.8 ACH (short dash), 3 ACH (alternating dash), 6 ACH (long dash), and 12 ACH (solid); for (e,f) outdoor exchange of 0% (short dash), 6% (alternating dash), 9% (long dash), and 33% (solid). The O mode for connected rooms overlaps the abscissa. The initial size distributions divided by the rational coefficient in Eq. 9 to enhance visual clarity consistent with Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Fig. A2. Approximated probability of infection for respiratory droplets of B (blue), L (red) and O (orange) modes in source room (a,c,e) and connected rooms (b,d,f) versus exposure times at 20 °C and 35% RH for cases in Table 3 following 5 min of viral shedding in the source room for (a,b) filtration levels of no filtration (short dash), MERV-8 filters (long dash), MERV-11 filters (alternating dash), and MERV-13 filters (solid); for (c,d) 1.8 ACH (short dash), 3 ACH (alternating dash), 6 ACH (long dash), and 12 ACH (solid); for (e,f) outdoor exchange of 0% (short dash), 6% (alternating dash), 9% (long dash), and 33% (solid). The O mode for connected rooms overlaps the abscissa. Modes evaluated independently at $M_i$ (B and L modes) or along diameter corresponding to the peak concentration (O mode). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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