Simulating the impact of ventilation on COVID-19 infection probability from aerosol transmission in enclosed spaces

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Abstract

Most people spend 80-90% of their lives indoors. This makes controlling the airborne transmission of respiratory viruses such as influenza, rhinovirus, SARS, and COVID-19 in indoor environments important for healthy building outcomes. Though direct transmission from droplets and surfaces is usually a more effective means of infection transfer, buildings need to operate assuming aerosol transmission can be a serious risk.

This study used simulations to assess the impacts of occupant density and ventilation rates as control measures to reduce the risk of aerosol transmission of COVID-19 in large and small offices. The simulation outputs were selected to correspond with in situ CO₂ sensors and control points. The results of the simulation can be used to set targets for CO₂ and other parameters that can be measured by low-cost sensors to manage risk of infection due to aerosol transmission.

Key Innovations

- Systematic evaluation of ventilation and occupant density as infection control strategies
- Linking infection probability to measurable outcomes for effective control.

Practical Implications

This simulation strategy applies only to aerosol transmission, and practitioners should consider that this is not the only transmission route. Rather, all else being the same, infection probabilities can be reduced with these actions. This data can be used to suggest evidence-driven back-to-work protocols for buildings based on their ventilation systems and number of occupants.

Introduction

An augmentation of the Wells–Riley equation (Rudnick and Milton, 2003) uses CO₂ concentration as a marker for exhaled breath exposure to determine the fraction (f) of inhaled air that has been exhaled previously by someone in the building from the volume fractions of CO₂ in indoor air (C), in outdoor air (C₀), and exhaled while breathing (Cₐ):

\[ f = \frac{C - C₀}{Cₐ} \]  

(1)

Coupled with the quantum generation rates of a virus (q) and the number of people likely infected in a space (I), and total people in a space (n), these concentrations can be used to model the risk of indoor airborne disease transmission in a space through the probability of infection (P):

\[ P = 1 - e^{\frac{-(Iarf)}{n}} \]  

(2)

Using simulated CO₂ readings for spaces of different size, occupant density, and ventilation rates, as well as known high and low quantum generation rates for several viruses, we were able to model the likelihood of airborne infection in a particular space and recommend various ventilation levels that decrease the risk of exposure and potential infection.

Methods

We used the CONTAM 3.2 software (Dols and Polidoro, 2015) to model two spaces indicative of small and large offices at various occupant densities and number of infectors, all with standard ceiling heights of 3 m (Table 1). The ambient outdoor CO₂ levels were set to 450 ppm.

Occupants were set to generate CO₂ at of 0.005 L/s with breathing rates of 8.0 L/min to represent low levels of activity and, therefore, oxygen consumption (Rudnick and Milton 2003). This gives a Cₐ of 0.038. Occupants were simulated in each space from 8 am to 5 pm for 7.25 non-consecutive hours (45-minute lunch break at 12 noon), indicative of typical office work.

Table 1: Simulation details – space, occupants, and infectors.

<table>
<thead>
<tr>
<th>Space Size (m²)</th>
<th>Occupants</th>
<th>Infectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>3</td>
<td></td>
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<td>25</td>
<td>4</td>
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<tr>
<td>30</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>50</td>
<td>1% of occupants</td>
</tr>
<tr>
<td>75</td>
<td>2% of occupants</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>5% of occupants</td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>10% of occupants</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>20% of occupants</td>
<td></td>
</tr>
</tbody>
</table>

To test the effect of different ventilation rates (Table 2), each simulation used a simple AHU set to one of four rates given in CIBSE Guide A (CIBSE, 2015). Results may vary for more complex HVAC systems that were not simulated in this study.
We simulated several viruses (SARS-CoV-1, influenza, etc.) as part of the study. The complete set of results, i.e., for all viruses, will be published separately. This paper shows the results for COVID-19 exposure, using a low and high quantum generation rate of 14 and 48 q/hr respectively (Dai and Zhao, 2020). While the COVID-19 quantum generation data is published, it is too new to be considered equally reliable to the figures for other viruses.

**Results**

The ranges of probabilities of infection for COVID-19 at IDA1 and IDA4 ventilation rates for the small (Figures 1-2) and large (Figures 3-4) spaces are shown here. The y-axis is the average of the probability over all working hours, while the x-axis is the increasing number or proportion of infectors. The solid lines represent the higher quantum generation rate, i.e., each infector exhales viruses at the maximum rate, while the dotted lines are for the lowest. The results below are reported as changes in average percentage probability, i.e., percentage points.

By increasing ventilation rates from 5 L/s/person (IDA 4) to 20 L/s/person (IDA 1), the probability of infection decreased anywhere from 22-32% (100m²) to 19-42% (500m²), over all the occupant densities. An increase in the number of infected people while the ventilation rate is held constant increased the probability anywhere from 2-25% (100m²) to 0.6-47% (500m²). When the occupant density was halved with all other factors kept the same, the infection probability decreased between 2-22% (100m²) and 0.3-4% (500m²).

**Conclusion**

There is a clear trend of increased viral infection probability with an increase in the number of infected people, and a decrease in the probability with an increase in ventilation. These results show the effectiveness of current social-distancing and ventilation-based virus control strategies, suggesting that by incorporating them into their back-to-work protocols an office could substantially lessen the risk of infection to its occupants. By quantifying effectiveness of these strategies in nominal office settings, our study suggests the potential to simulate more specific circumstances and use real-time CO₂ readings to give building-specific advice on ventilation rates and occupancy.

**References**


