

High efficacy of layered controls for reducing transmission of airborne pathogens

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In the past two decades, novel viruses capable of airborne transmission have emerged with alarming frequency, including SARS-CoV-1 in 2003, H1N1 in 2009, MERS in 2012, and SARS-CoV-2 in 2019. Yet, in many countries, controls on airborne transmission were not widely adopted until the COVID-19 pandemic. To optimize strategies for curbing the transmission of existing airborne viruses and to prepare for outbreaks of novel viruses in the future, the efficacy of three key controls — face masks, ventilation, and physical distancing — must be well understood. In this study, we used the new Quadrature-based model of Respiratory Aerosol and Droplets (QuaRAD) to quantify the efficacy of controls across thousands of scenarios that represent the wide variability in factors governing airborne transmission. We show that, while the efficacy of any individual control was highly variable among scenarios, the combination of universal mask-wearing and distancing of at least 1 m reduced the median risk of initial infection in the susceptible person by 99% relative to a close (0.5 m), unmasked conversation. Increasing ventilation rates by 4 air changes per hour led to further reductions in the median risk of infection by more than 70% if the two people were distanced by 2 m or more. The combination of face masks, distancing, and increased ventilation reduced the risk of infection by more than 98% in more than 95% of scenarios. These findings suggest that layering controls is highly effective for reducing transmission of airborne pathogens and will be critical for curbing outbreaks of novel viruses in the future.

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Introduction

The spread of SARS-CoV-2 led to rapid deployment of controls designed to limit airborne transmission. SARS-CoV-2, like influenza, measles, and tuberculosis, is transmitted predominantly through the inhalation of infectious particles (1). Controls like face masks, ventilation, and distancing reduce the likelihood that a susceptible person inhales virus-laden particles, but their efficacy depends on factors that are inherently variable and, often, poorly constrained (2). For example, rates of viral shedding, characteristics of expiratory jets, room conditions, and immune responses are all highly variable (2, and references therein). This uncertainty can be represented in models by simulating ensembles of scenarios, but models well-suited for simulating the evolution of respiratory particles in indoor spaces are often computationally expensive, limiting their representation of parametric uncertainty.

To represent the inherent variability in factors govern-

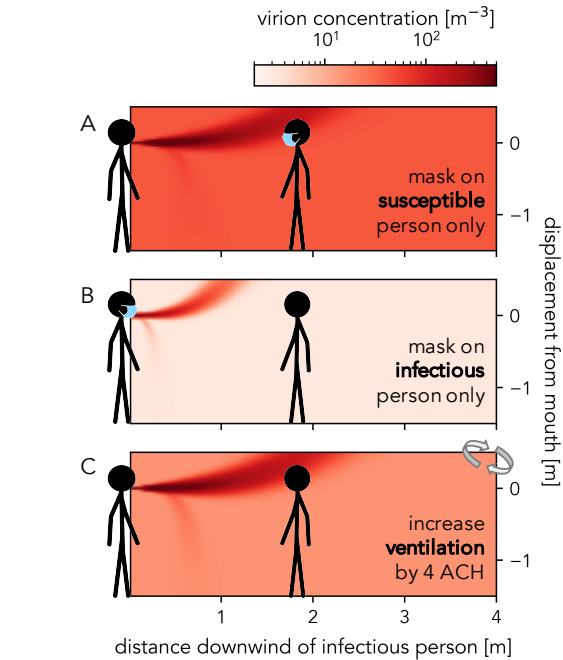


Fig. 1. Steady-state virion concentrations after a 3-hour, face-to-face conversation between an infectious person (left) and a susceptible person (right) in an example scenario. The susceptible person's exposure may be reduced if (A) they wear a mask, (B) the infectious person wears a mask, or (C) the ventilation rate is increased.

ing airborne transmission, we developed and applied the Quadrature-based model of Respiratory Aerosol and Droplets (QuaRAD) (2), an efficient framework for simulating the life cycle of virus-laden particles, from their initial creation in the respiratory system to their eventual removal from the room or deposition into the nasal cavity of a new host. QuaRAD simulates the evolution of respiratory aerosol and associated viral loads within indoor spaces by combining a quadrature-based aerosol model with a Gaussian puff dispersion model, where the Gaussian puff is propelled by the expiratory jet of the infectious person. Where possible, distributions in model parameters were constrained using measurements. As the viral loading within expired particles of different sizes has not yet been quantified for SARS-CoV-2, we used measured virion expiration rates for influenza (3), which has a viral shedding pattern similar to SARS-CoV-2 (4). These virion expiration rates were combined with measurements of respiratory aerosol size distributions (5) to estimate variation in viral loading with particle size. The par-

ticle size distribution, its evolution, and the resulting spatiotemporal variation in virion concentrations are simulated in QuaRAD using only six weighted particles. This efficient representation enables simulation of many cases that span the variability in model input parameters. The combined model predicts the risk of initial infection in a susceptible person as a function of their proximity to an infectious person and the duration of the encounter, which was used here to quantify the impact of controls on airborne transmission.

Results

Focusing on SARS-CoV-2, we simulated thousands of scenarios with QuaRAD to quantify the individual and combined efficacy of face masks, ventilation, and distancing. We focused on non-medical surgical masks only and applied the size-resolved mask efficiencies measured by (6), where the mask efficiency curve with respect to size was varied among scenarios to reflect the standard deviation of the measurements. To quantify changes in the risk of infection with ventilation, we simulated each scenario with its baseline (low) ventilation rate and at a ventilation rate elevated by four air changes per hour (ACH). The absolute ventilation rates for the high and low ventilation cases varied among scenarios, but the difference between the two ventilation rates was held to 4 ACH. This 4-ACH increase was chosen to approximately represent the impact of widely opening several windows (7), though the true impact of natural ventilation on ACH is highly variable depending on the particular building and the local meteorology. We focused on asymptomatic or presymptomatic transmission, with each scenario representing an infectious person speaking continuously in an indoor space for three hours. We first present the efficacy of face masks and ventilation in reducing initial infection in a susceptible person as a function of distance from an infectious person, then demonstrate the impact of combining these controls with social distancing.

Face masks and ventilation. An infectious person speaking in an indoor space expels virions that may be inhaled by someone else. The risk of transmitting infectious particles can be reduced through the use of face masks and ventilation, which is particularly important when infection rates of airborne viruses are high.

If a susceptible person is in a room with an infectious person, they may be exposed to high concentrations of virions (see Fig. 1a) depending on their respective locations and the conditions within the room. When the susceptible person wears a mask, their exposure to virions is reduced. The mask on the susceptible person captures some of the infectious particles, with an overall collection efficiency that depends on the size distribution of the particles and the size-resolved efficiency of the mask. The median risk of infection at the same distancing is reduced by 50% if the susceptible person is wearing a mask (Fig. 2a). However, this relative risk is highly variable, with 90% confidence intervals ranging from a relative risk of nearly 0 (eliminate risk entirely) to 1 (no change in risk). Unsurprisingly, we find this variability in efficacy is driven

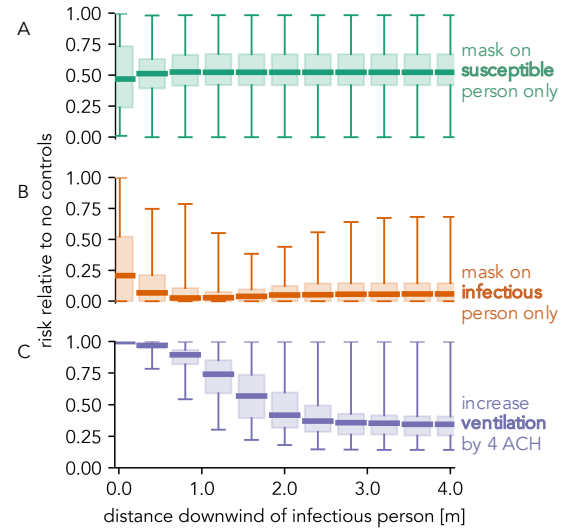


Fig. 2. Mean (solid line), quartiles (boxes), and 5%–95% confidence intervals (whiskers) in the relative risk of infection as a function of distance downwind of an infectious person when (A) the susceptible person wears a face mask and the infectious person does not, (B) the infectious person wears a face mask and the susceptible person does not, and (C) neither person wears a mask but ventilation is increased by 4 air changes per hour.

predominantly by variability in the relative performance of the mask, such that the relative risk decreases with increasing mask performance.

In general, mask use by the infectious person has greater benefits than mask use by the susceptible person (comparison between Fig. 2a and 2b), resulting from the larger collection efficiencies upon exhalation relative to inhalation (6). Mask use by the infectious person leads to a reduction in virion concentrations in their expiratory jet and throughout the room (see Fig. 1). Wearing a face mask also reduces the velocity of expelled particles (8), which reduces the horizontal extent of their expiratory jet (2). The efficacy of face mask use by the infectious person was also highly variable, again driven by the overall performance of the face mask.

Whereas face masks reduce the relative risk both near and far from an infectious person, the efficacy of ventilation in reducing transmission risk depends strongly on the distance between the infectious and the susceptible person. While many of the virions are carried in small particles that remain suspended and affect virion concentrations throughout the room, virion concentrations are greatest in the region directly downwind of the infectious individual. If the infectious person is unmasked, but the ventilation rate is increased by 4 ACH (Fig. 1c), far-field virion concentrations are reduced while concentrations in the expiratory jet of the infectious individual remain virtually unchanged. Consequently, increasing the ventilation rate does little to reduce near-field transmission. On the other hand, with distancing of 2 m or more, increasing the ventilation rate by 4 ACH reduces the median risk of transmission by more than 70%. Under these distanced conditions, the efficacy of increasing ventilation was highly variable among cases. This variability is controlled by the baseline ventilation rate and the volume of the room, where increasing ventilation tends to be most beneficial in small, poorly ventilated spaces.

Discussion

In this study, we showed that layered controls are highly effective in reducing transmission of airborne pathogens like SARS-CoV-2. The combination of social distancing, masking, and increasing ventilation led to a reduction in the median risk of infection by more than 99%. The efficacy of individual controls depends on the other controls that are in use. For example, ventilation reduces the risk of infection only when used in combination with social distancing; the risk of infection during a close conversation is governed by the near-field exposure to virions in the expiratory jet, which are not strongly impacted by the ventilation rate, but ventilation does impact long-range virion exposure. On the other hand, increasing distancing from 1 m (≈ 3 feet) to 2 m (≈ 6 feet) has a smaller impact when all parties are masked than when all are unmasked, which may explain the similarity in infection rates in schools with 3-foot and 6-foot distancing between masked students (9). Without universal masking, increasing distancing from 1 m to 2 m is critical for minimizing the risk of infection.

We showed that variability in the efficacy of face masks among scenarios was controlled predominantly by the overall mask efficiency, suggesting that mitigation strategies should encourage not only widespread use of masks, but use of masks that are efficient and well-fitting. Measurements show that surgical masks tend to have higher collection efficiencies than microfiber or cotton masks (6, 10), while layering a surgical mask with a cotton mask has been shown to be even more effective (11). Reductions in risk will likely be greater than reported in this study if either party is wearing an N95 respirator (10) or layering a well-fitting cotton mask on top of a non-medical surgical mask (12).

These findings suggest that many lives lost to COVID-19 could have been prevented with earlier and wider adoption of controls on airborne transmission. Further, the lack of controls during the COVID-19 pandemic has enabled SARS-CoV-2 to mutate to form variants that are more severe, more infectious, and better able to evade immune defences, vaccinations, and treatments (13) — if the virus is not transmitted, it cannot replicate; if it cannot replicate, it cannot mutate. Wide adoption of layered controls could dramatically reduce transmission of existing airborne viruses, such as SARS-CoV-2, and will be critical to control outbreaks of novel airborne viruses in the future.

Methods

Quadrature-based model of Respiratory Aerosol and Droplets. QuaRAD is an efficient framework for simulating the evolution of virus-laden particles after they are expired from an infectious individual, the deposition of these particles to the nasal cavity of a new host, and the resulting risk of initial infection. The model replaces the continuous aerosol and droplet size distribution with a quadrature approximation of six weighted particles (2). For each particle, the model simulates changes in particle size and virion viability as a function of time, and dispersion of each quadrature point is

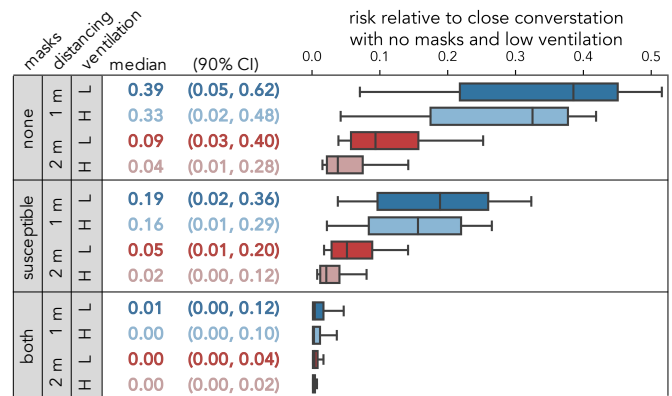


Fig. 3. Median (solid line), quartiles (boxes), and 90% confidence interval (whiskers) of the risk of initial infection when employing different combinations of controls relative to the risk of initial infection during a close (0.5 m) conversation at the baseline (low) ventilation rates, computed from 2000 scenarios. The median and 90% confidence intervals of the relative risk are also shown in the adjoining table.

simulated using a Gaussian puff within a turbulent jet model. The combined model is used to predict the size distribution of virus-laden particles and its spatiotemporal evolution, which is used to predict the virion exposure to a new host as a function of their location relative to the infectious person and the duration of the encounter. For a given viral dose, we then predict the risk of initial infection. A detailed description of QuaRAD, including references for key model components, is provided in (2). The model is available open source at <https://github.com/lfierce2/QuaRAD>.

Ensembles of scenarios to represent uncertainty in model input parameters. To represent the wide range of conditions within indoor spaces and the wide variety of physiological properties among the general population, we performed thousands of model simulations with QuaRAD. We used Latin Hypercube Sampling from the Python Design of Experiments library (<https://pythonhosted.org/pyDOE/>) to sample uncertainty in model input parameters, where the distributions from which input parameters were sampled are given in (2). In each scenario, the size distribution of respiratory aerosol was represented by three superimposed lognormal modes that correspond to sites of origin in the respiratory system, following (5). The size distribution parameters and, consequently, quadrature points and weights were varied between scenarios. The viral load of particles in each mode was estimated by combining the size distribution measurements of (5) with measurements of virion number from (3), such that the assumed viral loads were also varied to represent variation in measurements. Parameters of the expiratory jet and room conditions were also constrained using measurements, where possible, as described in (2).

The baseline scenario was the same as the baseline scenario in (2), but the ventilation rate in this study was adjusted to the

ensemble median of 1.5 air changes per hour.

D_p (μm)	CE_{in}	σ_{in}	CE_{out}	σ_{out}
0.5	0.3084	0.1745	0.4206	1.159
0.7	0.3209	0.1745	0.6542	0.9657
1	0.3489	0.1682	0.7227	0.7913
2	0.4953	0.1620	0.7570	0.6729
5	0.8691	0.1059	0.9283	0.1495

Table 1. Mean and standard deviation (σ) of collection efficiency (CE) of a surgical mask measured in (6). Surgical masks also reduce expiration velocity by an average of 53% ($\sigma = 0.12$) (8).

Quantifying efficacy of controls in each scenario. In each scenario, we compared the risk of initial infection in the susceptible person for cases without controls (low ventilation, no masks) and for cases with different combinations of controls, and quantified the impact of distancing in Fig. 3 by comparing the risk of infection at 1 m or 2 m with the risk of infection at 0.5 m. We adjusted input parameters within QuaRAD to represent the impact of controls on transmission rates. To simulate a susceptible person wearing a mask while an infectious person is not, we assumed that some of the particles, depending on their size, were captured in the mask; these captured particles are unable to deposit into the nasal cavity of the susceptible person and cause infection. To estimate the size-dependent collection efficiency upon inhalation, we used the measurements from (6). (6) provides the mean and standard deviation of mask collection efficiency at each size. Using these distributions, we represented a separate mask collection efficiency curve for each scenario. To ensure continuous efficiency curves with respect to size, we assumed the relative performance (in terms of standard deviations from the mean) was the same for each scenario. Similarly, we represented a face mask on the infectious person by modifying the number of virus-laden particles that are expelled, according to the scenario- and size-dependent mask collection efficiency upon exhalation, where the mask efficiency upon exhalation was also estimated from (6). We represented the reduction in expiration velocity according to measurements by (8), while also adjusting the effective diameter of the jet orifice to maintain the same flow rate. Increasing the ventilation rate was represented by modifying the removal rate in the wall reflection terms in QuaRAD (2).

Global sensitivity analysis. To identify the variables that most affect variability in efficacy of an individual control, we used the global sensitivity indicator δ of (14). Under this framework, $\delta = 0$ indicates no dependence of the output parameter on the input parameter, whereas $\delta = 1$ if uncertainty in the output is explained entirely by a combination of model parameters. We computed δ using the Sensitivity Analysis Library in Python (<https://salib.readthedocs.io/en/latest/>).

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