Respirators, face masks, and their risk reductions via multiple transmission routes for first responders within an ambulance

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ABSTRACT

First responders may have high SARS-CoV-2 infection risks due to working with potentially infected patients in enclosed spaces. The study objective was to estimate infection risks per call for first responders and quantify how first responder use of N95 respirators and patient use of cloth masks can reduce these risks. A model was developed for two scenarios: a ride with a patient actively emitting a virus in small aerosols that could lead to airborne transmission (scenario 1) and a subsequent ride with the same respirator or mask use conditions, an uninfected patient, and remaining airborne SARS-CoV-2 and contaminated surfaces due to aerosol deposition from the previous ride (scenario 2). A compartmental Monte Carlo simulation model was used to estimate the dispersion and deposition of SARS-CoV-2 and subsequent infection risks for first responders, accounting for variability and uncertainty in input parameters (i.e., call duration, transfer efficiencies, SARS-CoV-2 emission rates from infected patients, etc.). Infection risk distributions and changes in concentration on hands and surfaces over time were estimated across sub-scenarios of first responder respirator use and patient cloth mask use. For scenario 1, predicted mean infection risks were reduced by 69%, 48%, and 85% from a baseline risk (no respirators or face masks used) of $2.9 \times 10^{-2} \pm 3.4 \times 10^{-2}$ when simulated first responders wore respirators, the patient wore a cloth mask, and when first responders and the patient wore respirators or a cloth mask, respectively. For scenario 2, infection risk reductions for these same scenarios were 69%, 50%, and 85%, respectively (baseline risk of $7.2 \times 10^{-3} \pm 1.0 \times 10^{-2}$). While aerosol transmission routes contributed more to viral dose in scenario 1, our simulations demonstrate the ability of face masks on patients to additionally reduce surface transmission by reducing viral deposition on surfaces. Based on these simulations, we recommend both the

patient and first responders wear cloth masks and respirators, respectively, when possible, and cleaning should prioritize high use equipment.

INTRODUCTION

The COVID-19 pandemic has highlighted the importance of understanding and mitigating viral transmission in indoor environments, especially in those that are high risk because infectious persons are likely to be present, such as in healthcare facilities and emergency response vehicles. COVID-19 transmission is likely to occur via multiple routes including large droplet spray depositing on mucous membranes, inhalation of aerosols across a range of sizes (Port et al. 2020; Tang et al. 2020; Miller et al. 2020) and fomite transmission via contaminated hands and surfaces (Xie et al. 2020; Port et al. 2020). While the relative contributions of these routes have been debated (The Lancet Respiratory Medicine 2020), the importance of aerosols is increasingly clear based on the biological and physical plausibility of aerosol transmission (Jones and Brosseau 2015; Tang et al. 2020), the characteristics of COVID-19 outbreaks (Miller et al. 2020; Tang et al. 2020), animal studies (Port et al. 2020), and models estimating exposures from multiple routes (Jones 2020). Regardless of their relative contributions, the aerosol and fomite transmission routes are related: Infectious respiratory aerosols may deposit or settle on surfaces and can later become resuspended or transfer to the mucous membranes via hands. The characteristics of a small and enclosed environment can amplify exposures through both routes quickly.

Emergency medical services (EMS) vehicles are small, enclosed environments in which SARS-CoV-2 exposures are likely, owing to the transport of COVID-19 patients and shortages or imperfect use of personal protective equipment (PPE) (Murphy et al. 2020). Such exposures can strain EMS services through increased medical leave for quarantine, isolation and treatment, and psychosocial stress (Murphy et al. 2020; Prezant et al. 2020; Ehrlich et al. 2020). For example, an MS2 tracer study demonstrated that virus surrogates can spread extensively via hand-to-surface contacts in EMS vehicles, contaminating 56% (27/48) of surfaces within an EMS vehicle (Valdez et al. 2015), but the frequency and magnitude of exposures via aerosol and fomite transmission routes remain unknown. The objective of this study was to estimate infection risks for EMS personnel in vehicles caring for COVID-19 and non-COVID-19 patients through the aerosol and fomite routes and explore the benefit of cloth masks worn by patients, respiratory protection worn by first responders, and masks or respirators worn both parties.

METHODS

Scenarios

The study explores the exposure of first responders to SARS-CoV-2 through the fomite and aerosol transmission routes. Droplet (aerosols >5 μm) transmission was not considered in the primary analyses because of the high prevalence of asymptomatic COVID-19 cases among COVID-19 cases, roughly 40-45% (Oran and Topol 2020), the fact that only about 50% (Salepci et al. 2020) of symptomatic cases experience cough symptoms, and prevalence of cloth mask use, which would decrease droplet emission. While speech does generate aerosols >5μm, the majority are likely less than 5μm in size (Alsved et al. 2020). Two exposure scenarios were considered: Scenario 1.) the first patient in the EMS vehicle has COVID-19 and emits respirable aerosols (≤5 μm) containing SARS-CoV-2, and Scenario 2.) a second patient in the vehicle following the first patient does not have COVID-19, but there are aerosols containing SARS-CoV-2 in the air and contamination on fomites from deposition of aerosols from the previous (scenario 1) ride (Table 1). For both scenarios, four sub-scenarios were explored based on respirator and cloth mask use patterns: A.) Neither the first responders nor the patient is wearing respirators or cloth mask, respectively, B.) First responders are wearing respirators, but the patient is not wearing a cloth mask, C.) The patient is wearing a cloth mask, but the first responders are not, and D.) Both the first responders and patient are wearing respirators and a cloth mask, respectively (Table 1). This resulted in 8 total scenarios (2 virus source scenarios x 4 respirator scenarios) (Table 1).

It was assumed that patients did not introduce contamination directly to fomites via hand-to-surface contacts, and it was assumed first responders were not contaminated at the start of the simulation. Since recommended PPE for first responders includes gloves, this assumption was deemed reasonable. For Scenario 2, due to uncertainty regarding time in between rides, initial virus concentrations on surfaces and in air were based on the virus concentrations at the end of scenario 1, given the same respirator scenario. For example, for scenario 2B (first respirators with respirators and patient without a mask), the initial conditions were determined from the final virus concentrations in scenario 1B.

Sensitivity Analyses

While it was assumed patients wore cloth masks, source control efficacy likely varied widely owing to different mask materials and fit. To evaluate how infection risk reductions for first responders would be affected by a wide range of source control efficacies for patient masks, the relationship between mask source control effectiveness and infection risk for first responders without masks or respirators was quantified. Specifically, scenario 1C was modified to include a wide range of mask effectiveness (10% to 90%) for the patient. A linear relationship was fit to $\log_{10}$ infection risks for first responders vs. mask efficacy for the patient.

While droplet spray transmission is not modeled, a second sensitivity analysis was performed to explore the influence of droplet spray on fomite-mediated infection risks in scenario 2 simulations. This was motivated owing to concern that by excluding virus contamination that could arise from droplet emission in scenario 1, fomite-mediated exposures may be underestimated. The initial surface contamination was varied to explore how much was necessary for the contact transmission route and the aerosol inhalation route to contribute equally to dose and subsequent infection risk. The fraction of emitted droplets that would need to deposit to yield infection risks for scenarios where the patient was not wearing a respirator (scenarios 2A and 2B) being as large as for scenario 1A was explored.

To evaluate whether this level of surface contamination was feasible, the amount of virus that would be emitted through patient coughs droplets (≥ 100 μm) likely to deposit rapidly onto nearby surfaces over a 20 minute ride in an EMS vehicle was tabulated. Description of this calculation can be found in Supplemental Materials. The surfaces included in the model were considered nearby, however, it is acknowledged that other surfaces could be near patients in EMS vehicles as well that are not accounted for in this model.

Discrete Markov Chain Model

A discrete Markov chain modeling approach was utilized to model exposures and subsequent risks of infection (Jones 2020; Weir et al. 2016). States in which SARS-CoV-2 was tracked included frequently touched fomite surfaces expected in EMS vehicles, including headphones, portable radio, jumpbag handle, touchscreen, glucometer, and computer keyboard; the respiratory tracts of two paramedics; mucosal membranes of two paramedics; the respiratory tract of the patient; room air; exhaust; and inactivation of the virus in air, on gloved hands, and on surfaces (Figure 1). First-order rates of transition from one state to another were estimated, and a Monte Carlo approach was used to account for variability and uncertainty in these rates. The number of iterations and the timestep used per scenario were determined by comparing mean and median infection risks and patterns of temporal changes in virus loads in selected compartments estimated for 10,000 vs. 1,000 iterations and 0.01- vs. 0.001-minute timesteps. It was determined that 1,000 iterations and 0.001-minute timesteps resulted in consistent patterns of concentration changes and similar mean and median infection risks while balancing computational costs. Therefore, 1,000 iterations per scenario with 0.001-minute timesteps were conducted. Spearman correlation coefficients were calculated to quantify monotonic relationships between model parameters (inputs) and the modeled $\log_{10}$ infection risk (output), focusing on comparisons between scenarios 1 and 2 and when both first responders and patients wore respirators.

Emission of Virus into Air

The amount of virus emitted by the patient into air was assumed to be continuous during scenario 1. Virus emission varies widely among people, with stage of infection and with respiratory activity (Johnson et al. 2011; Cevik et al. 2021). The emission rate of virus in respirable particles (≤5 µm) was represented by a triangular distribution over the range of 10^0 to 10^5 virus per 30 minutes (Table 2) informed by graphically-presented seasonal coronavirus emission among human subjects without the use of masks (Leung et al. 2020). Particles transferred to the respiratory tracts of first responders via inhalation resulted in doses.

Transition of Virus between Surfaces and Hands

The rate of transfer of SARS-CoV-2 from surfaces to hands, $\lambda_{surface,hands}$ (/min) was calculated as:

$$\lambda_{surface,hand} = \frac{1}{SA_{surface}} \cdot S_H \cdot TE_{surface,hand} \cdot A_{hand} \cdot H_{surface} \cdot f_{surface} \qquad (1)$$

Where, $SA_{surface}$ is the fomite surface area (cm^2), A_{hand} is the surface area of the hand (cm^2), S_H is the fraction of A_{hand} involved in the contact (unitless), $TE_{surface,hands}$ is the surface-to-hand transfer efficiency (unitless), $H_{surface}$ is the frequency of contact with surfaces (#/min) and

$f_{surface}$ is the fraction of surface contacts that occur with this surface. The rate of transfer of SARS-CoV-2 from hands to surfaces ($\lambda_{hands,surface}$) was calculated as:

$$\lambda_{hands,surface} = \frac{1}{2} \cdot S_H \cdot TE_{hands,surface} \cdot H_{surface} \cdot f_{surface} \qquad (2)$$

Where, $TE_{hands,surface}$ is the hand-to-surface transfer efficiency (unitless), and other variables are as previously defined. Note that hand-to-surface transfer does not involve an area adjustment because the surface area of the state is equal to the surface area of both hands.

Transfer efficiency has not yet been measured for SARS-CoV-2 or other coronaviruses, to our knowledge. Therefore, MS2 transfer efficiencies measured with ungloved fingertips for nonporous surfaces under low relative humidity conditions were used (Lopez et al. 2013). Transfer efficiency was assumed to be reciprocal (Julian, Leckie, and Boehm 2010), $TE_{hands,surface} = TE_{surface,hands}$. Gloves have been shown to lower transfer efficiency for multiple organisms (Greene et al. 2015; King et al. 2020), although gloved hands could become more contaminated if the gloves do not fit properly by increasing available surface area for contacts than what would be available for ungloved hands (King et al. 2020). Since it was assumed that first responders were wearing gloves, we reduced $TE_{hands,surface}$ and $TE_{surface,hands}$ by 61% (King et al. 2020), and transfer efficiencies were represented by a Uniform distribution over the range of 0.0061 to 0.248 (Table 2).

For hand-to-surface contacts, the fraction of the hand used in the contact, S_H, was informed by fractions of a hand used for a single fingertip contact up to a full front palm with fingers configuration (AuYeung et al. 2008). The minimum fraction measured for adults' right hands for partial front palm without fingers, which was slightly smaller than the minimum for front partial fingers, was divided by 5 to estimate the fraction of surface area used for a single fingertip touch or a contact with a portion of the palm (0.006). This value along with the maximum fraction of the hand used for a full front palm with fingers configuration was used to inform the minimum and maximum values of a Uniform distribution (Table 2) (AuYeung et al. 2008).

The frequency of hand-to-surface contacts, $H_{surface}$, was informed by observed rates of hand-to- surface contacts made by healthcare workers during actual care of patients (King et al. 2021) (Table 2). These contacts were then apportioned among the six surface states (Figure 1) based on relative contamination levels observed in a viral tracer study, where contamination was driven by hand-to-surface contacts (Valdez et al. 2015) (Table 2). This approach was motivated by the finding of Adams et al., that the frequency of hand-to-surface contacts was linearly associated with microbial contamination (Adams et al. 2017). More details are found in the Supplemental Materials. Fomite surface areas were also informed by Valdez et al. (2015) and are shown in Table 2.

Transition of Virus from Hands to Facial Mucosal Membranes

The rate of transfer during hand-to-mucosal membrane contacts, $\lambda_{hands,mucosal\ membrane}$ (/min), was calculated as:

$$\lambda_{hands,mucosal\ membrane} = \frac{1}{2} \cdot S_F \cdot TE_{hands,face} \cdot H_{face} \tag{3}$$

Where S_F is the fraction of the total hand surface area used for hand-to-face contacts (unitless), $TE_{hands,face}$ is the hand-to-face transfer efficiency (unitless), and H_{face} is the frequency of hand-to-face contacts (#/min).

The distribution for S_F was informed based on an assumption that a single fingertip or a small portion of the palm with a similar surface area as a fingertip would be used in the contact (Table 2), and more details are available in the Supplemental Materials. Contact frequencies with the face when respirators were not worn were informed by face contact rates reported in healthcare contexts for masked and unmasked individuals, respectively, where less frequent hand-to-face contact was associated with mask usage (Lucas et al. 2020), consistent with another study (Chen et al. 2020). Hand-to-face transfer efficiencies were informed by Rusin et al. (2002), where a normal distribution was used, truncated to the range of 0-1 (Table 2). Since the standard deviation was not reported in the original work, the data for the study were revisited to quantify the standard deviation in viral hand-to-mouth transfer efficiency.

Transition of Virus from Air to Respiratory Tracts

The rate at which virus in room air moves into the respiratory tract owing to inhalation, $\lambda_{room\ air,respiratory\ tract}$, (/min) was calculated as:

$$\lambda_{room\ air,respiratory\ tract} = \frac{I}{V_{room\ air}} \quad (4)$$

where $V_{room\ air}$ (m^3) is the volume of air in the EMS vehicle and I is the inhalation rate (m^3/min). When respirators or face masks were worn, the rate at which virus in room air is inhaled is reduced by the complement of the respirator or mask effectiveness, M (unitless),

$$\lambda_{room\ air,respiratory\ tract} = \frac{1}{V_{room\ air}} \cdot I \cdot (1 - M) \quad (5)$$

The volume of the ambulance air was estimated by using measurements of the back cab space and accounting for a side table, chair on the left side of the vehicle, bench on the right side of the vehicle, and chair in the center of the vehicle. Notes on these dimensions and on the distribution for inhalation rates (Table 2) are in Supplemental Materials. N95 FFR effectiveness was modeled by using a beta distribution to describe penetration (Nicas 1994) (Table 2). N95 FFR effectiveness is the compliment of penetration, and the beta distribution was fit to reproduced measured performances of a variety of N95s (Coffey et al. 2004): The mean penetration and effectiveness are 27.3% and 72.7%, respectively. Cloth mask effectiveness was modeled by using a beta distribution, with mean 50.9%, and used to represent both outward protection (source control) and inward effectiveness (Lindsley et al. 2021).

For first responders, doses due to inhalation were equal to the total amount of virus that transitioned from room air to the respiratory tract over the simulation period. While the fraction and location of inhaled particles that deposit in the lungs depend upon particle size, this was neglected as we did not distinguish particle sizes below 5µm. The assumption that all particles deposit in the lungs, and contribute to dose, provides a conservative risk estimate.

Transition of Virus from Air to Exhaust

The air within the vehicle was assumed to be fully well mixed and governed by the fresh air exchange rate. The rate of virus loss from the vehicle air owing to the air exchange rate, $\lambda_{room\ air,exhaust}$(/min), was equal to:

$$\lambda_{room\ air,exhaust} = AER \tag{6}$$

where AER is the rate of fresh air exchange (/min).

Transition of Virus from Air, Hands, or Fomites to Inactivation

The virus inactivation rate in air was randomly sampled from a triangular distribution (Table 2) that was previously utilized in a SARS-CoV-2 risk assessment (Jones 2020) and based on laboratory studies SARS-CoV-2 inactivation in air (van Doremalen et al. 2020). For inactivation on hands, it was assumed that first responder hands were gloved. We used an approach described by King et al. (2020), where a uniform distribution was used for T_{99} values, or the time it takes to see a 2 $\log_{10}$ reduction (King et al. 2020) (Table 2). An inactivation constant was estimated, where $\lambda = -\log(1/10^2)/T_{99}$. For inactivation on surfaces, an approach described by King et al. (2020) was used, where a range of times representative of half-lives were used to estimate λ.

Transition of Airborne Virus to Surfaces

Given the focus on respirable aerosols, the gravitational settling rate was represented as a triangular distribution with mode of 28.80 day^{-1}, the theoretical setting rate of a particle with aerodynamic diameter of 4 µm (Stilianakis and Drossinos 2010). Owing to the variability in the size of respiratory aerosols and influence of humidity, and deviation of the actual settling rate from the theoretical rate, we considered that the settling rate could vary 25% relative to the mode (Table 2).

Model Simulation

Rates describing transitions from state *i* to state *j* were first summed to calculate a total rate of transition away from state i. The probability that a virus in state *i* remains in state *i* after one time step, Δt, is denoted $P_{i,i}$, and is calculated as:

$$P_{i,i} = e^{-\lambda_{Ti}\Delta t} \quad (7)$$

Where λ_{Ti} equals the sum of all first-order loss rates affecting state i. The probability that a virus in state *i* moves to state *j* in one time step, $P_{i,j}$, calculated:

$$P_{i,j} = \left(1 - P_{i,i}\right)\left(\frac{\lambda_{i,j}}{\lambda_{Ti}}\right) \quad (8)$$

The values $P_{i,i}$ and $P_{i,j}$ for i, j = {1, 2, ….16} states are tabulated, and arranged into a one-step transition probability matrix **P**. The model is then simulated by iterative multiplication of **P** for the number of time steps in the scenario duration. Given scenario duration T (min), then n = T/ Δt time steps. More detail on the mathematical operations in the Markov model are provided elsewhere (Nicas and Sun 2006). The model was simulated over the duration of an EMS ride, represented by a triangular distribution over the range of 5 to 20 minutes with mode 12.5 minutes (Table 2). The model time step was Δt = 0.001 min.

Infection Risks

Infection risk ($P_{infection}$) was estimated using an exact beta-Poisson dose-response curve fit to pooled SARS-CoV-1 and human coronavirus 229E (HCoV229E) dose-response data (Watanabe et al. 2010; Bradburne, Bynoe, and Tyrrell 1967; DeDiego et al. 2008):

$$P_{infection} = 1 - {}_1F_1(\alpha, \alpha + \beta, -d) \quad (9)$$

Where α and β are used in pairs (bootstrapped pairs available in the code associated with this work), d is cumulative dose from the aerosol and fomite routes estimated from the Markov model, and ${}_1F_1$, is the Kummer confluent hypergeometric function (Xie et al. 2017). This dose-response curve has been used in other risk assessments for COVID-19 (Wilson et al. 2020; King et al. 2020). Dose-response for SARS-CoV-2 has not yet been measured.

RESULTS

Modeled infection risks to first responders were greatest when a COVID-19 patient was present and not wearing a face mask along with first responders not wearing respirators (Scenario 1A, Figure 2): The average infection risk was 2.9 x 10^{-2} (SD=3.4 x 10^{-2}). For scenario 2A, when there was no COVID-19 patient present, but residual infective SARS-CoV-2 was present in air and on surfaces, the average infection risk was smaller, 7.2 x 10^{-3} (SD=1.0 x 10^{-2}). When both the patient wore a face mask and first responders wore respirators, average infection risks for scenarios 1D and 2D were reduced to 4.5 x 10^{-3} (SD=7.4 x 10^{-3}) and 1.1 x 10^{-3} (SD=1.9 x 10^{-3}), respectively.

For scenario 1A, when SARS-CoV-2 was being emitted into the air and neither the patient was wearing a face mask nor first respirators wearing respirators, the inhalation route was estimated to contribute to 98% of SARS-CoV-2 dose, while the fomite route only contributed 2% (for 12.5 minutes of exposure); these percentages were fairly consistent over the duration of simulations with fomites contributing a slightly greater percentage to dose as the duration of the call increased. When first responders wore respirators (scenario 1B), the inhalation route and fomite routes contributed to 97% and 3% of dose, respectively. These percentages were the same for scenario 1D, when both patients wore face masks, and first responders wore respirators. Increases in dose due to inhalation versus fomite-mediated exposures (hand-to-face contacts) for scenarios 1A-D can be seen in Figure 3. For scenario 1, when SARS-CoV-2 was being emitted into the air, average infection risks were reduced by 69%, 48%, and 85% when simulated first responders wore respirators (scenario 1B), the patient wore a face mask (scenario 1C), and when both first responders wore respirators and the patient wore a face mask (scenario 1D), respectively, relative to infection risks when no one wore a respirator or face mask (scenario 1A).

For scenario 2, in which residual airborne SARS-CoV-2 and SARS-CoV-2 was present on surfaces, infection risk was influenced by face mask use by patients and respiratory use by first responders in the previous ride (scenario 1), because the use of respirators in the prior ride influenced the initial level of airborne and surface concentrations. After 12.5 minutes in scenario 2, in scenarios where respirators were not used by first responders (scenarios 2A and 2C) the inhalation route was estimated to contribute 88% of dose while the fomite route contributed 12%. When respirators were used by first responders, the inhalation route contributed 81-82% to dose while the fomite route contributed 18-19% (scenarios 1B and 1D). In scenario 2, respirator use not only reduced inhalation exposure but also was assumed to decrease the rate of hand-to-face contacts. Considering both effects, scenario 2 infection risk was reduced by 69% when first responders wore respirators (scenarios 1B and 2B), by 50% when the patient wore a face mask (scenarios 1C and 2C), and 85% when first responders wore respirators and the patient wore a face mask (scenarios 1D and 2D), relative to no face mask or respirator use (scenario 2A).

For scenario 1, emissions had the strongest monotonic relationship with $\log_{10}$ infection risk (ρ=0.77). First responder respirator efficacy had one of the strongest monotonic relationships with $\log_{10}$ infection risk in scenario as well (scenario 1: ρ = -0.37), where greater respirator efficacy was related to lower $\log_{10}$ infection risk (Table 3). For scenario 2, the association between patient mask efficacy and infection risk depended upon the amount of virus present on the surfaces at the start of the exposure scenario (Figure 4). When only the patient wore a face mask and the first responders did not in scenario 1C, a Spearman correlation coefficient of -0.12 was observed. However, when neither the first responders nor patient wore respirators (scenarios 1A and 2A) or when only the simulated first responders wore respirators (scenarios 1B and 2B), the relationships between respirator efficacy and $\log_{10}$ infection risk for scenario 2 were weaker (scenario 2A: ρ = -0.0023, scenario 2B: ρ = -0.02). This supports the hypothesis that patient mask use and its impact on aerosol deposition in scenario 1 likely drove the negative relationship with infection risks estimated for scenario 2.

In the sensitivity analysis to investigate the influence of patient mask effectiveness on infection risk of first responders, increased mask efficacy decreased infection risk, where the linear fit line had a slope of 1 and an R^2 of 1.00 (Figure S3). The y-intercept of -0.944 indicates that patient mask effectiveness is generally slightly higher than the anticipated risk reduction for first responders in this model (Figure S3).

In the sensitivity analysis to evaluate the amount of surface contamination necessary to make the doses through the fomite and aerosol routes equivalent, the virus load on surfaces (#viral particles/surface) needed to be 19.07 to 1502, on average (Figure S4). This virus surface load could be obtained by a deposition of 2.07% to 163% of total droplets greater than 100 µm generated by patient coughs over a 20-min ride, assuming 1% of genome copies relates to infective virus. It should be noted that the fraction of genome copies that represents infective virus was an influential parameter on estimated infection risks (scenario 1: ρ = 0.35, scenario 2: ρ = 0.34) (Table 3).

DISCUSSION

Consistent with other work, this study demonstrated that the aerosol route is likely a primary driver of COVID-19 risk in enclosed spaces (Miller et al. 2020; Jones 2020), and face masks can reduce viral emissions from the patient and N95 FFRs can reduce exposure among first responders. Face covering use reduced mean infection risks (by 48% to 85% on average) in scenario 1, with the greatest risk reduction benefits occurring when both the patient and first responders were wearing cloth masks and respirators, respectively (scenario 1D). The value of source and receptor controls through face coverings has been demonstrated in other studies (Brooks et al. 2021).

When N95 FFRs were worn by first responders in the simulated scenarios 1B, the aerosol transmission route contributed to 97% of the total dose, as opposed to a slightly larger contribution of the aerosol transmission route (98%) when first responders did not wear respirators and more virus was therefore inhaled. When Scenario 1C was expanded to include a wider range of mask efficacies for the patient, mask effectiveness had a linear relationship with infection risk reduction among responders (Figure S3), meaning that less effective face coverings on patients has less benefit for first responders. The filtration effectiveness of mask materials has been shown to vary widely by material type (Pan et al. 2020). Given a mask effectiveness, it is possible to estimate the risk reduction expected in the scenarios modeled in this study using Figure S3.

This study has demonstrated that while the aerosol transmission route may contribute more to dose than the fomite route, the aerosol and fomite transmission routes are related. Interventions aimed at reducing the emission of aerosol virus may also provide benefits for reducing fomite-mediated exposures by decreasing viral deposition on surfaces, as shown by the decreased surface contamination at the end of scenario 1C when the patient wore a mask (Figure 4) and the 50% reduction in infection risk in scenario 2C. Interventions like respirators also prevent facial mucous membrane contact, interrupting the fomite transmission route.

When the patient wore a face mask (scenario 1C), as opposed to the first responders wearing respirators and the patient without a face mask (scenario 1B) the infection risk reductions were less (48% vs. 69%, respectively), due to lower effectiveness of the cloth mask compared to respirators (Table 2). The risk reductions were similar in scenario 2, where patient use of a mask during scenario 1C reduced infection risks by 50% in scenario 2C, and first responder respirator use in scenarios 1B and 2B reduced infection risks by 69%. The reduction in airborne SARS-CoV-2 and viral deposition on surfaces as a result of patient mask use explains a portion of the infection risk reduction in scenario 2. In the scenarios in this study, first responders were assumed to not have COVID-19. However, respirator use by first responders could offer source control benefits for reducing risks to uninfected patients and other first responders, if a first responder was infected.

When respirators were used by the first responders and a mask was used by the patient during care of a COVID-19 patient (scenario 1D), infection risks for care of COVID-19 patients were low (mean=4.5×10^{-3}, SD=7.4×10^{-3}) relative to scenario 1A (mean=2.9×10^{-2}, SD=3.4×10^{-2}) where no masks were used with a COVID-19 patient. Murphy et al. reported 0.4% (3/700) emergency medical services (EMS) staff testing positive for COVID-19 after an encounter with a

COVID-19 patient (Murphy et al. 2020). However, there was no documentation of occupational exposures for these three positive cases (Murphy et al. 2020). Higher COVID-19 risks have been observed among EMS responders in other studies, where Prezant et al. reported 13% of EMS responders (573/4408) being on medical leave due to being a confirmed COVID-19 case (Prezant et al. 2020). Sami et al. found that 22.5% of first responders tested positive for antibodies specific to SARS-CoV-2, where 38.3% of medical emergency technicians (EMTs) tested positive (Sami et al. 2021). In comparison to EMTs, paramedics had lower seroprevalence, possibly due to required additional training requirements relative to EMTs (Sami et al. 2021). It is unknown whether these individuals were infected due to an occupational or community exposure, and Sami et al. reported exposure to COVID-19 household members as being associated with higher odds of seropositivity (Sami et al. 2021). Adjusted odds ratios for PPE use, including N95 FFRs, were insignificant, with the exception of gloves that was associated with greater odds of seropositivity, potentially indicating the importance of proper PPE use and safe donning and doffing practices (Sami et al. 2021). While the estimated risks in this modeling study were lower than some of these reported rates, risks from this study are for individual rides with a patient. Repeated rides and interactions with infected patients would lead to increased risks. Additionally, the ambulance ride is only one component of potential exposures for first responders, where they may also be exposed in the patient's home or in a public space where first contact is made.

Because this model framework assumes that air is well mixed, the higher concentration of aerosols that may be expected within the immediate exhaled breath plume (Vuorinen et al. 2020) are not accounted for; the results here are likely to be an underestimate for face-to-face exposure within 1m of the patient for the cases where the infectious patient is not wearing a respirator

(Scenarios 1A and 1B). A potential intervention for reducing risks of aerosol transmission in between patients may include leaving the ambulance doors open to increase fresh air in the back of the vehicle. Extensions of the model developed here could be used to explore a variety of airflow conditions and durations of open ambulance doors to evaluate the efficacy of this intervention for reducing aerosol exposures in between patient rides.

It is assumed in this work that contacts to the mouth, eyes, and nose contribute to the cumulative dose via indirect contact transmission. While there is evidence supporting the potential for SARS-CoV-2 to be transmitted via hand-to-mouth contact (Xie et al. 2020), there is uncertainty as to whether contacts with the mouth, eyes, or nose contribute equally to infection risk and what fraction of transferred virus may reach an infection initiation site. Therefore, risks from these contacts in this model are likely overestimates. More data are needed describing mechanisms of infection initiation from hand-to-mucosal membrane contacts to improve estimates of dose via the indirect contact route. Additionally, the inactivation of airborne virus or virus on surfaces during time between scenarios 1 and 2 was not accounted for due to uncertainty in the duration between calls. A conservative approach was therefore taken, assuming that there was no virus loss between calls, which may result in overestimates of airborne and fomite risks in scenario 2. The effect of inactivation between calls or behaviors regarding common disinfection or ventilation practices between calls could be used in future model advancements to address this uncertainty.

When PPE is in short supply, other practices to reduce COVID-19 transmission risks include prioritizing the use of PPE for high-risk calls. For example, in King County, Washington, USA, PPE practices before February 28, 2020 were determined by “high-risk criteria” that included febrile respiratory illness paired with either travel from an area with a high number of

COVID-19 cases or a known encounter with a COVID-19 confirmed case (Murphy et al. 2020). These high-risk criteria were further refined after February 28th when calls from long term care facilities (LTCFs) were determined to be high risk and would require "mask, eye protection, gown and gloves" (MEGG) (Murphy et al. 2020). Such recommendations have been informed by previously developed guidance and lessons learned from medical transport, including aeromedical evacuation (Nicol et al. 2019), during other highly infectious disease outbreaks, such as for Ebola (Centers for Disease Control and Prevention 2015). Modeling studies can facilitate evaluation of these guidelines by providing quantitative and scenario-based insights, highlighting areas of uncertainty and the impact of potential interventions, such as components of MEGG in reducing risk. This could further define criteria for balancing limited PPE supplies and potential risks due to encounters with COVID-19 patients.

Another limitation of this work is uncertainty in viral emission rates. With regard to viral emission rates, we have based our model on measured data for seasonal coronaviruses (Leung et al. 2020) in the absence of adequate data for SARS-CoV-2. Studies have shown that viral loads vary significantly between people with COVID-19 (Cevik et al. 2021) and modeling studies suggest this could result in a range of viral emissions spanning several orders of magnitude (Buonanno et al. 2020; Miller et al. 2020). The viral emission rate will affect the absolute risks of infection predicted and could result in an under or over-estimate of risk. However, in comparing relative effects, the viral emission rate is of less importance as the same assumption is applied across all the modeled scenarios. This is true for other limitations of the model, such as uncertainty in time between rides and subsequent inactivation, environmental conditions and impacts on inactivation, mechanisms of infection via hand-to-facial mucosal membrane contacts, etc. While these limitations reduce confidence in the interpretation of estimated absolute risks, because these limitations are consistent across scenarios, the risk reduction comparisons between interventions remain valuable for informing intervention implementation.

CONCLUSIONS

Mask use for the patient and respirator use for first responders are effective means to reduce first responder SARS-CoV-2 infection risks. While mask use is most effective in terms of risk reduction when a patient is actively emitting airborne SARS-CoV-2, its use by patients, may also reduce viral deposition on surfaces, reducing fomite transmission risks for future rides. More scenario-specific hand-to-face contact frequency data are needed to improve the developed model.

RECOMMENDATIONS

Based on these simulations, it is recommended that both the patient and first responders wear masks and respirators, respectively. The results of this simulation show that there is a slight advantage when first responders use N95 FFR over cloth mask use by patients, due to differences in device effectiveness, but there is additional benefit to responders from the use of masks by patients. While risks from surface contamination are small in this study, effective cleaning of surfaces, particularly frequently used equipment will result in a further reduction in COVID-19 risk for responders.

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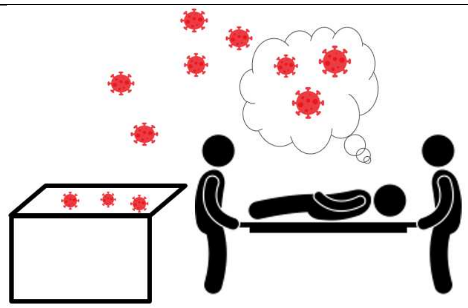
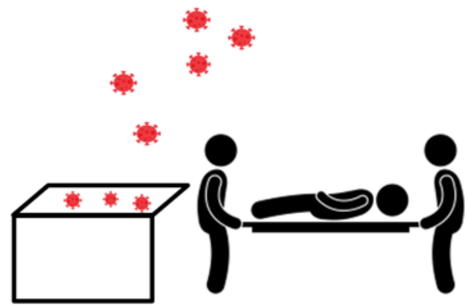
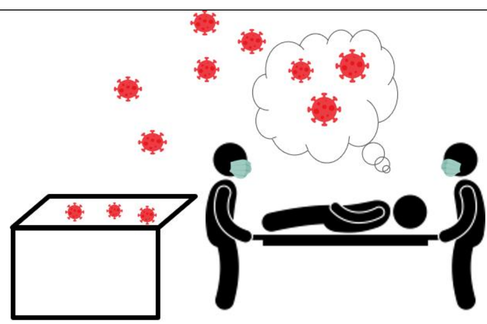
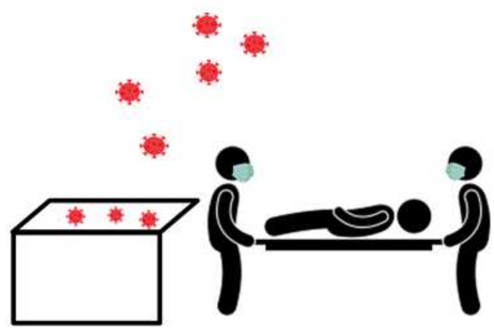
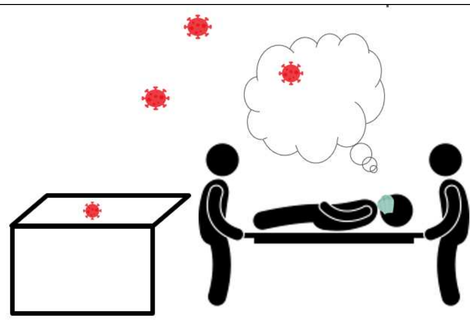
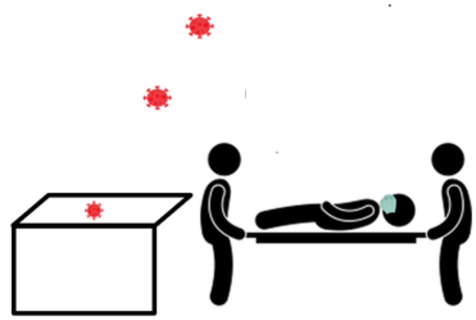
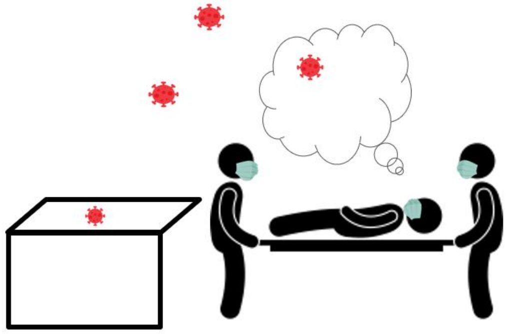
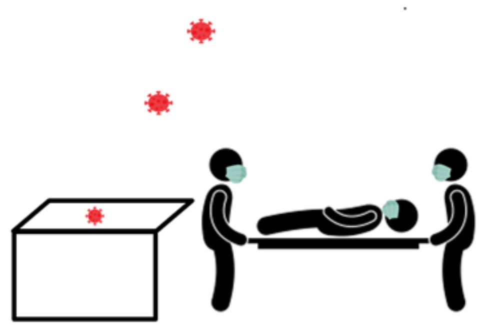
FIGURES AND TABLES

Table 1. Simulation scenario descriptions*

		t →	
		Scenario 1	Scenario 2
Respirator Scenarios		COVID-19 patient actively emitting SARS-CoV-2 in exhaled breath	Non-COVID-19 patient and air and surfaces are contaminated at the start of the call due SARS-CoV-2 emissions during scenario 1
A	First responders not wearing respirators and patient not wearing a mask		
B	First responders are wearing respirators, but the patient is not wearing a mask		
C	The patient is wearing a mask, but the first responders are not wearing respirators		

D	Both the patient is wearing a mask and first responders are wearing respirators		

*Respirator and mask conditions were held constant for each scenario 1 and scenario 2 sequence, where viral concentrations on surfaces and in air at the end of scenario 1 informed starting concentrations on surfaces and in air for scenario 2

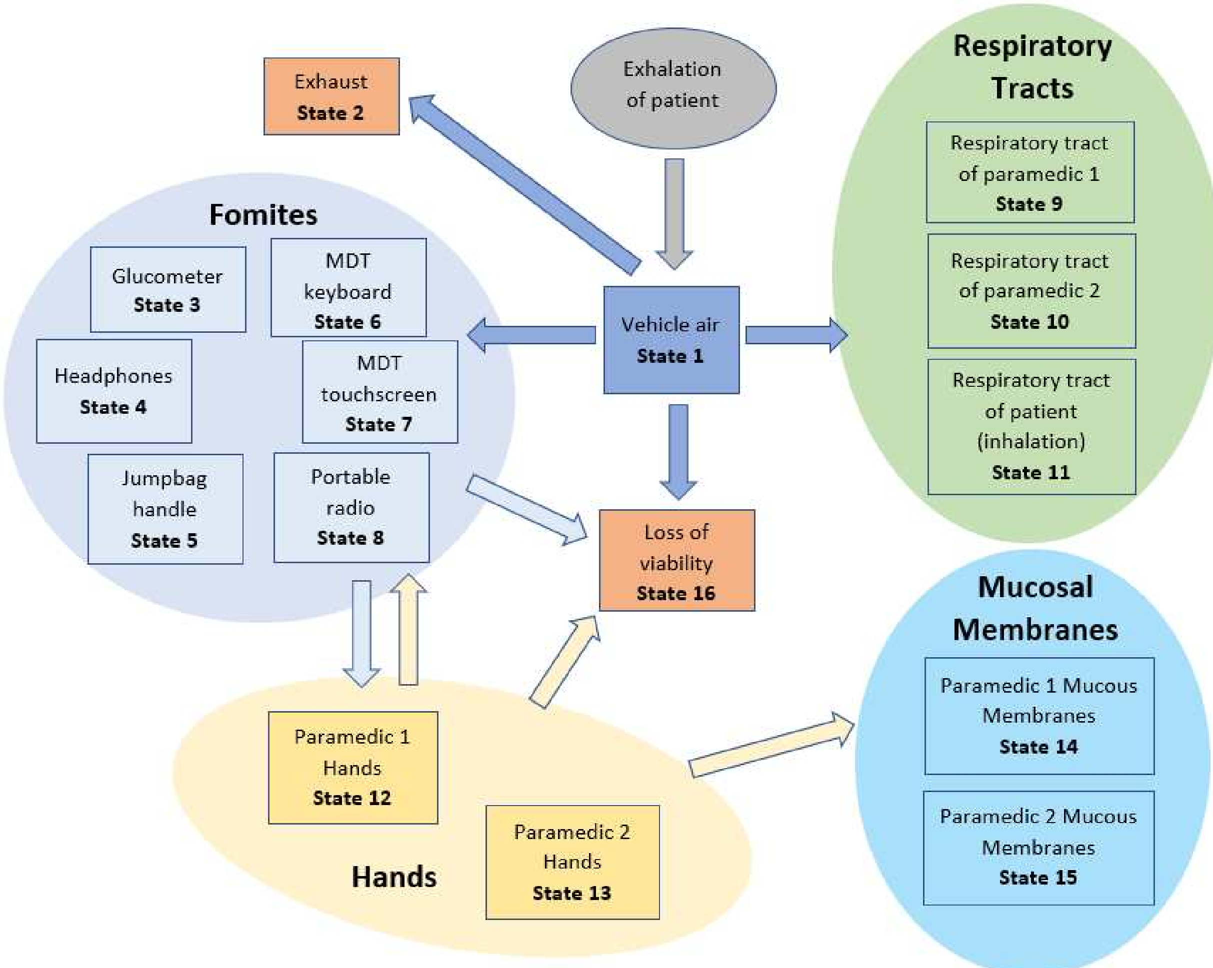


Figure 1. Identifying states and transitions between state types

Table 2. Distributions and point values for model parameters and their sources

Description		Variable	Distribution/point value	Source
Hand-to-surface transfer efficiency (fraction)		$TE_{hands,surface}$	Uniform (min=0.0061, max=0.248)	(King, López-García, et al. 2020; Lopez et al. 2013)
Surface-to-hand transfer efficiency (fraction)		$TE_{surface,hands}$		
Hand-to-facial mucosal membrane transfer efficiency		$TE_{hands,face}$	Normal (mean=0.3390, sd=0.1318) Range 0-1	(Rusin, Maxwell, and Gerba 2002)
Frequency of hand-to-surface contacts for both hands		$H_{surface}$	Normal (mean=10.3, sd=3.4), contact/min Range 5-16	(King et al. 2021)
Probability of hand-to-fomite specific contact given contact with nonporous surface	Glucometer	$f_{surface}$	0.03	(Valdez et al. 2015), This study
	Headphones		0.44	
	Jumpbag handle		0.14	
	MDT keyboard		0.32	
	MDT touchscreen		0.05	
	Portable radio		0.04	
Fomite surface areas	Glucometer	$SA_{surface}$	7.8 cm^2	(Valdez et al. 2015)
	Headphones		148.44 cm^2	
	Jumpbag handle		141.95cm^2	
	MDT keyboard		305.64 cm^2	
	MDT touchscreen*		65.52 cm^2	
	Portable radio		50.84 cm^2	
Frequency of hand-to-face contacts with respirators		$H_{faceresp}$	Triangular (min=2.3, mode=5.4, max=17.8), contacts/hr	(Lucas, Mustain, and Goldsby 2020)
Frequency of hand-to-face contacts without respirators		H_{nose}	Triangular (min=12.8, mode=20, max=22.9), contacts/hr	
Fraction of total hand surface area	Hand-to-surface contact	S_H	Uniform (min=0.006, max=0.24)	(AuYeung, Canales,

used for contact				and Leckie 2008)
	Hand-to-facial mucosal membrane contact	S_F	Uniform (min=0.006, max=0.012)	(AuYeung, Canales, and Leckie 2008)
Total hand surface area		A_{hand}	Uniform (min=445, max=535), cm^2	(U.S. Environmental Protection Agency 2011; Beamer et al. 2015)
Inactivation rates	Fomites	$\lambda_{3,16}$, $\lambda_{4,16}$, $\lambda_{5,16}$, $\lambda_{6,16}$, $\lambda_{7,16}$, $\lambda_{8,16}$	Uniform (min=0.085, max=0.151), hr^{-1}	(King, Wilson, et al. 2020; van Doremalen et al. 2020)
	Air	$\lambda_{1,16}$	Triangular (min=0.096, mode=0.253, max=0.420), h^{-1}	(Jones 2020; van Doremalen et al. 2020)
	First responders' hands (gloved)	$\lambda_{12,16}$, $\lambda_{13,16}$	Uniform (min=0.77, max=4.61), hr^{-1}	(Sizun, Yu, and Talbot 2000; King, Wilson, et al. 2020)
Air exchange rate		AER	Uniform (min=12, max=32) air changes h^{-1}	(Lindsley et al. 2019; Seitz, Decker,

			and Jensen 1996)
Volume of ambulance	$V_{room\ air}$	9.9 m^3	This study
Inhalation rate	I	Normal (mean=2.6 x 10^{-2}, sd=6.0 x 10^{-3}), m^3/min Left-truncated at 1.4 x 10^{-2}	(U.S. Environmental Protection Agency 2011)
Respirator Efficacy for First Responders	$M_{responder}$	Penetration Beta (α= 3, β=8)** 1-Penetration = Respirator Efficacy	(Nicas 1994; Coffey et al. 2004)
Cloth Mask Efficacy for Patient	$M_{source\ control}$	Beta (α= 20.9, β=20.2)**	(Lindsley et al. 2021)
Gravitational settling	$\lambda_{1,3}, \lambda_{1,4}, \lambda_{1,5}, \lambda_{1,6}, \lambda_{1,8}$	Triangular (min=21.60, mode=28.80, max=36), day^{-1}	(Stilianakis and Drossinos 2010)
Emission rate	A	Triangular (min=10^0, mode=10^0, max=10^5), viral particles/30 min	(Leung et al. 2020)
Fraction of genome copies representative of infectious virus	-	Uniform (min=0.001, max=0.01)	Assumed
Duration of call	-	Triangular (min=5, mode= 12.5 max=20), min	Assumed

*Assuming the MDT touchscreen has the same surface area as the EPCR touchscreen reported by Valdez et al. (2015)
**When relating these to parameters described by Nicas (1994) (Nicas 1994), $\alpha = k, \beta = n - k + 1$.

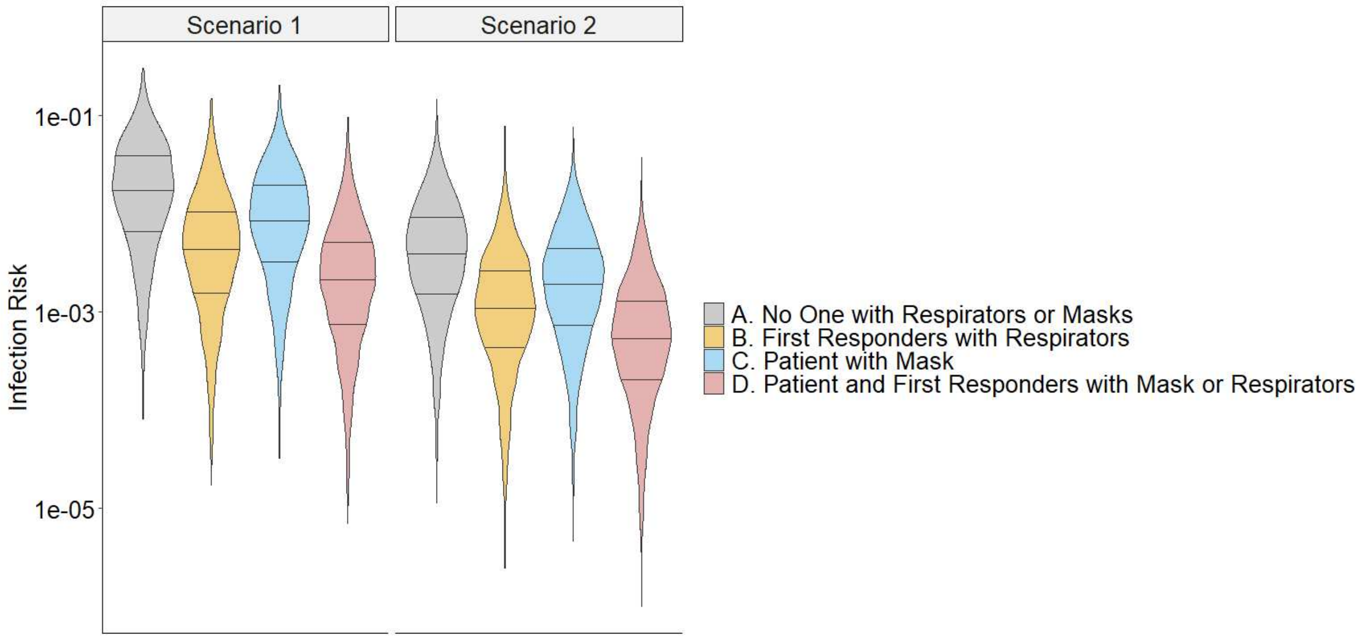


Figure 2. Distributions of estimated infection risks for first responders. Scenario 1 included an infectious COVID-19 case emitting aerosol into an EMS vehicle that had no initial virus contamination. Scenario 2 started with fomite and air contamination and involved no aerosol emission.*

*Lines are the 25th, 50th, and 75th quantiles.

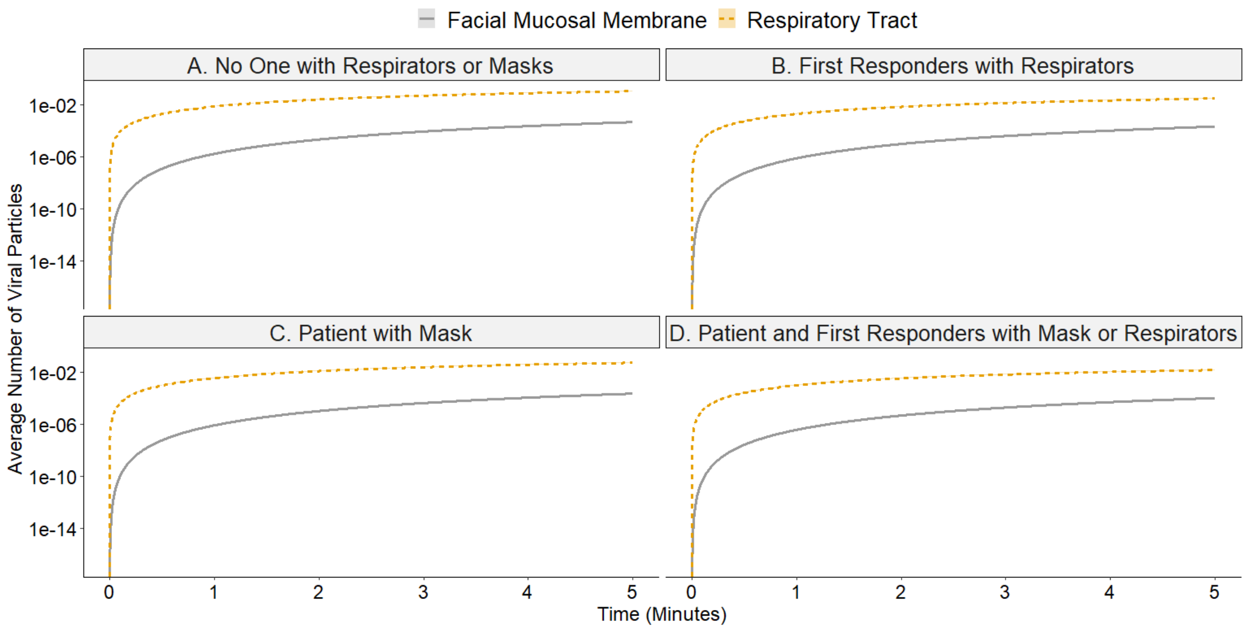


Figure 3. Dose of SARS-CoV-2 to the facial mucosal membranes and respiratory tract of a first responder over time for scenario 1.*

*The lines depict the mean, and shaded area the 95% confidence interval of simulation results, where there were 1,000 iterations per scenario. Number of viruses is less than one due to these being the average number of viral particles estimated to be inhaled into the respiratory tract or transferred to the facial mucosal membranes over the simulated time duration

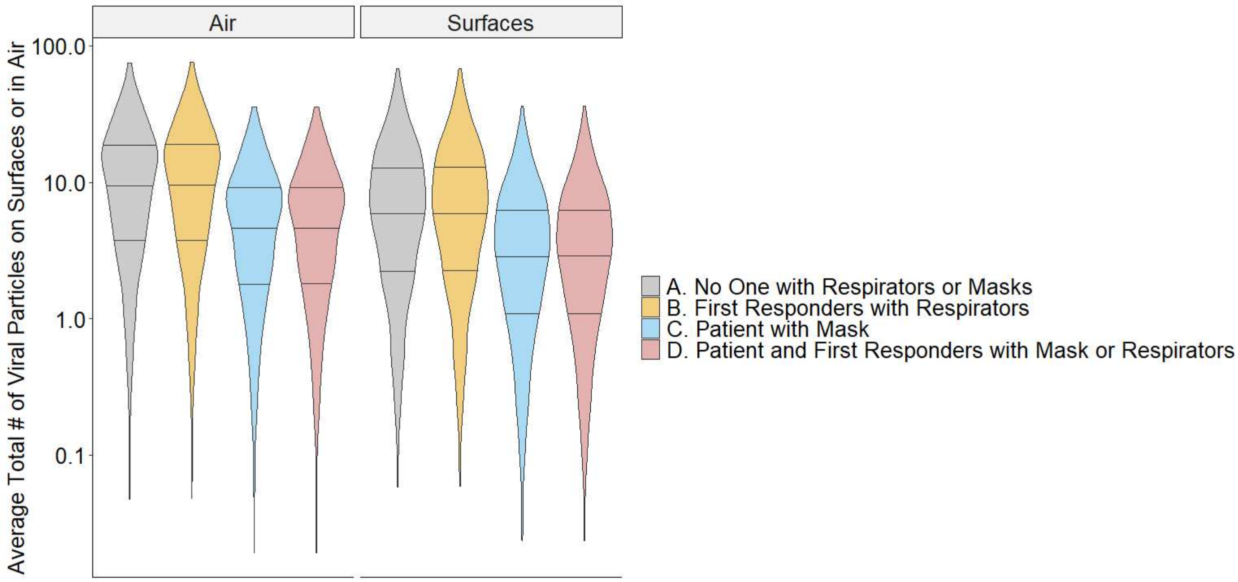


Figure 4. Total amount of virus on all surfaces at the end of scenarios 1A-D and beginning of scenario 2A-D simulations*

*Number of viruses can be less than one due to these being the average number of viral particles estimated to be on surfaces over the simulated time duration. Lines are the 25th, 50th, and 75th quantiles.

Table 3. Spearman correlation coefficients for scenarios 1 and 2 when the simulated patient wore a mask and first responders wore respirators

	Scenario 1	Scenario 2
Hand-to-surface transfer efficiency	0.020	0.045
Surface-to-hand transfer efficiency	0.041	0.070
Hand-to-mouth transfer efficiency	0.046	0.097
Surface contact frequency	0.014	-0.00061
Face contact frequency	-0.075	-0.0043
Fraction of hand used in surface contacts	-0.0077	0.027
Fraction of hand used in face contacts	-0.040	-0.0071
Total hand surface area	0.0018	0.0024
Viral inactivation rate on surfaces	-0.028	-0.025
Viral inactivation rate in air	0.013	0.032
Fraction of RNA that relates to infectious virus	0.35	0.34
Viral inactivation rate on hands	0.037	0.028
Inhalation rate	0.17	0.15
Mask efficacy for the patient as source control	-0.11	-0.14
Respirator efficacy for first responders	-0.37	-0.30
Air exchange rate	-0.14	-0.27
Beta (dose-response curve parameter)	-0.33	-0.32
Alpha (dose-response curve parameter	-0.22	-0.21
Emission rate	0.77	*

*Emission rates were set to zero for scenario 2