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Simulation of SARS-CoV-2 Aerosol Emissions in the Infected Population and Resulting Airborne Exposures in Different Indoor Scenarios

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ABSTRACT

Some of the SARS-CoV-2 virus can become airborne. Estimates suggest that the exhaled viral emissions from an infected person with high viral load can result in critical airborne concentrations in poorly ventilated small rooms. This project aimed to develop an indoor scenario simulator to rapidly assess the potential exposure in different indoor situations. It uses the estimates of a Monte Carlo simulation for the viral emission strength of breathing, speaking softly and loudly. The resulting emitter strength feeds a near-field far-field well-mixed room model. The indoor scenario simulator allows testing different room and ventilation sizes, wearing different masks, and different levels of physical activity and speech types for different percentiles of emitter strength in the population. The scenario tests suggest that in typical situations such as moderately ventilated offices, small shops, trains, buses, or carpool, very high emitters (99th percentile and above) not wearing masks are likely to cause concentrations with an elevated risk of infection via aerosols, especially in the near-field of the infected person. Speaking loudly and high levels of physical activity further increase the concentrations. If all persons wore surgical (hygiene) masks or filtering respirators with a higher protection factor, the expected concentrations were low in most situations, even if the viruses were released by "super-emitters" (top 1 permille emitter). This indoor scenario simulator may be helpful for decision makers as well as workplace and facility experts to assess and improve existing protection concepts, and to guide indoor exposure assessment campaigns.

Keywords: SARS-CoV-2, Exhaled aerosol, Indoor air, Scenario simulator, Inhaled dose

1 INTRODUCTION

In late 2019, a new form of coronavirus disease (COVID-19) emerged in China and rapidly spread throughout the world (Coronaviridae Study Group of the International Committee on Taxonomy of Viruses, 2020). Three routes of transmission for this virus called SARS-CoV-2 seem most relevant: by contact of contaminated surfaces, by directional spray processes of large droplets expelled during coughing, sneezing and speaking, and by a fogging-like process from exhaled small aerosols released from breathing and speaking but also sneezing and coughing (Chu *et al.*, 2020; Jones, 2020; Riediker, 2020). Faecal transmission was also proposed (Tian *et al.*, 2020) but not yet documented to actually occur. A particularity of SARS-CoV-2 is that it seems to be spread to an important part by people who are not yet or never symptomatic of COVID-19 (Furukawa *et al.*, 2020). Research suggests a community transmission rate of about 10 to 15% (Li *et al.*, 2020) and a secondary household attack rate in the range of 35% (Liu *et al.*, 2020a), which suggests that transmission is driven by a relatively small number of individuals. Indoors, airborne transmission seems to be very important (Zhang *et al.*, 2020), as evidenced also by numerous "superspreading" events where one person infected many others present in the same room even when respecting distancing and hygiene rules. Indeed, in hospitals with COVID-19 patients, the virus was detectable in the air (Liu *et al.*, 2020b)

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The dose necessary to infect humans is subject to ongoing research. For many viruses, a few hundred to a thousand plaque forming units (PFU) are sufficient to infect a human (Schröder, 2020; Yezli and Otter, 2011). For SARS-CoV-1 (the epidemic that started in 2002), it was suggested that at a dose of 280 plaque forming units, 50% of the people would get infected, while the lowest dose that infected somebody was estimated at 16 PFU (Watanabe *et al.*, 2010). For SARS-CoV-2 (causing COVID-19 in the current coronavirus epidemic), virologists estimate that the infective dose is in a similar range though slightly higher than for SARS-CoV-1 (Chandrashekar *et al.*, 2020; Karimzadeh *et al.*, 2020; Pfeifferle *et al.*, 2020; Schröder, 2020). PFUs are not identical to the number of viral copies determined by polymerase chain reaction (PCR), since several hundred „virus copies“ can be present per PFU (Sampath *et al.*, 2005). When aiming to prevent infections, a "critical dose" that should not be exceeded can be defined as a few PFU, which probably corresponds to a few hundred viral copies determined by PCR. Research on the minimal infective dose of SARS-CoV-2 is ongoing and may still move this "critical dose" up or down.

Earlier, we showed that the risk of having elevated, potentially infectious concentrations of SARS-CoV-2 in the air seems to depend strongly on the viral load in the lung lining liquid that is released into the air (Riediker and Tsai, 2020). The viral load in sputum and nasal swabs determined by PCR was reported to range from a few hundred viral copies per millilitre to over 10^{10} copies mL^{-1} (Lou *et al.*, 2020; Wölfel *et al.*, 2020; Zheng *et al.*, 2020; Zou *et al.*, 2020).

The aim of this study was to develop a tool for the rapid simulation of scenarios of SARS-CoV-2 transmission through aerosols under different indoor conditions. It starts with a refined analysis of the ability of a SARS-CoV-2 infected person to emit the virus by simulating the virus-emission source strength distribution in the general population. Input variables of this simulator are the virus emitter strength, loudness of speech, physical activity of emitter and exposed person, room characteristics such as room size, ventilation rate and average wind speed, and types of masks worn by emitter and exposed person. The output produced are estimates of the concentration and inhaled dose in the room and near the emitter.

2 METHODS

We modelled the distribution of the viral emission strength in the population with a Monte Carlo simulation: we started by randomly sampling the viral load of a person from the distribution in the general population published in a preprint (Jones *et al.*, 2020) and used it to calculate the virus concentration contained in the different sizes of exhaled microdroplets. This base viral emission was next combined with a random draw from the distribution of the ratio of the emitted aerosol compared to the median amongst people reading a text at loud voice (Asadi *et al.*, 2019), specifically a log-normal distribution with a geometric mean of 0.982 and a geometric standard deviation of 1.964. We then approximated the amount that is likely to stay airborne for prolonged time in turbulent air by retaining in each size fraction what would pass through an inhalable particulate matter (PM_{10}) impactor, as described earlier (Riediker and Tsai, 2020). The resulting emission strength was finally scaled to talking quietly (25% larger and 5x in number compared to being quiet) and loudly (10x in number compared to talking quietly) using published difference factors (Asadi *et al.*, 2019). This Monte Carlo simulation was repeated 100,000 times. It provided the emission strength distribution for low, median, high, very high and super-emitters, corresponding to the 10th, 50th, 90th, 99th percentile, and 999th permille, respectively.

The exposure in the room was modelled with a deterministic mass balance near-field far-field well-mixed room model (Nicas, 2016) with a spherical near-field and an interzonal flow rate defined by the half globe surface and the average wind speed in the room (Keil and Zhao, 2017). It uses the above-defined emission strengths for different percentiles of quiet, low or loud speech (in virus per cm^3 emitted air) combined with the respiratory volume. The respiratory volume was defined for sitting/resting at $7500 \text{ cm}^3 \text{ min}^{-1}$, for low activity at $15,000 \text{ cm}^3 \text{ min}^{-1}$ and for high activity at $45,000 \text{ cm}^3 \text{ min}^{-1}$ (Ramos *et al.*, 2015). The inactivation of the virus in the air was addressed by including the published half-life of the 50% tissue culture infective dose of aerosolised SARS-CoV-2 (van Doremalen *et al.*, 2020) as a decay term. Filtering facepiece respirators were assumed to pass fit testing and were assigned the minimally required retention efficiency of 80% for FFP1, 95% for FFP2 and 99% for FFP3. For the exhalation efficiency, respirators without

valve were arbitrarily assigned a factor of 80%, since they were qualitatively described to be slightly better at reducing the exhalation flow than surgical masks (Hui *et al.*, 2012; Milton *et al.*, 2013), while those with a valve were given a retention efficiency of 5% at exhalation. A mini-review of the exhalation and inhalation efficiencies of surgical masks and simple cloth face coverings (Table 1) suggested the inhalation and exhalation retention efficiency of well-fitting surgical/hygiene masks to be 75%, and that of simple single-layer cloth face coverings to be 25%.

The indoor scenario simulator allows a user to modify the following input parameters: the room volume, the air exchange rate (AER), the average air speed in the room, the time spent by an infected person in the room, the types of masks worn by infected people and bystanders, the type of emitter (from low to super-emitter), the physical activity, the loudness of speech, and the critical dose of virus copies (determined by PCR) that should not be exceeded. AER was defined as the rate of replacing the indoor air by virus-free air, either high-efficiency filtered or fresh outdoor air.

The output parameters of the simulator are the estimated viral levels in the far-field (the background in the room) and the near-field (within 60 cm of the emitter), the cumulative inhaled number of viruses at these two locations and the time until a critical virus dose is reached for different physical activities of the bystander.

The simulator provides the exposure and inhaled dose of a bystander who enters the room at the same time as the emitter, thus at the beginning of the build-up of the room concentration. To obtain the inhaled dose of a bystander entering a room where an infected individual already spent time, one needs to simulate two time points: t_1 = (the time spent by the emitter until the bystander enters), and the time $t_2 = t_1 +$ (the time spent by the bystander), to obtain the dose (late entering) = dose(t_2) – dose(t_1). The simulator is available in the online supplementary data.

For defining scenarios in public transport, we obtained volumes and AER from Swiss public transport providers. Worst-case assumptions for AER in naturally ventilated offices were based on federal work inspector observations, while long-distance bus and airplane data were taken from public sources (major manufacturer websites and Wikipedia). Car volumes and AER correspond to mid-size (large family) vehicles, as described in a representative sampling study in Californian cars (Fruin *et al.*, 2011). We also tested scenarios that were documented as super-spreading events in the literature (Hamner *et al.*, 2020; Hijnen *et al.*, 2020; Lu *et al.*, 2020; Park *et al.*, 2020). The room sizes were estimated from the descriptions given in the papers and from

Table 1. Retention efficiency of face coverings, community masks and surgical masks described in the literature.

Source	Mask type	Exhalation retention	Inhalation retention	Testing conditions
(He <i>et al.</i> , 2013)	Surgical mask	not assessed	65% to 90%	Manikin head, multiple breathing rates
(Wen <i>et al.</i> , 2013)	Surgical masks	not assessed	60% to 85% (filtering material itself > 95%)	Manikin head
(Milton <i>et al.</i> , 2013)	Surgical masks	70% to 74% (fine to total aerosol)	not assessed	Viruses exhaled by influenza patients
(Zangmeister <i>et al.</i> , 2020)	Different layers and cloth types	20% to 32% (one layer)	20% to 32% (one layer)	Filtration efficiency only, no fit test
(Rengasamy <i>et al.</i> , 2010)	Different cloth types	10% to 60%	10% to 60%	Filtration efficiency only, no fit test
(Davies <i>et al.</i> , 2013)	Surgical mask	85% (airborne)	60% to 89%	Human exhalation with microbe test, fit test for inhalation
(Davies <i>et al.</i> , 2013)	Homemade mask	78% (airborne)	50% to 60%	Human exhalation with microbe test, fit test for inhalation
(Checchi <i>et al.</i> , 2005)	Surgical mask	not assessed	85 to 86%	Manikin head
(Bałazy <i>et al.</i> , 2006)	Surgical mask	not assessed	15% to 80%	Manikin head
(Li <i>et al.</i> , 2006)	Surgical mask	not assessed	95%	Human exposed to KCl aerosol

online identified pictures showing the locations. To test whether airborne transmission was a plausible explanation, we erred to the “healthy side” and assumed AER to be 3 exchanges per hour, which is in the upper range of what can be expected in such places.

The Monte Carlo statistics were calculated using Stata/SE 15.1 (StataCorp, College Station, TX, USA). The indoor scenario simulator was implemented using Excel 365 for Mac (Microsoft, Redmond, WA, USA) without macros and by using only formulas that are in use for at least 15 years. Compatibility tests were done using Excel 2016 for Windows (Microsoft, Redmond, WA, USA), LibreOffice 6.3 for Windows, Mac and Linux (The Document Foundation), and Numbers 10.1 for Mac (Apple Inc, Cupertino, CA, USA).

3 RESULTS AND DISCUSSION

3.1 Monte Carlo Modeling of Viral Emitter Strength

The Monte Carlo simulation provided the estimated distribution of the viral emitter strength for breathing only, speaking quietly/normally and speaking loudly. Fig. 1 shows the input distributions and the resulting estimated distribution while speaking quietly, which is multimodal and skewed to the left. Table 2 shows the key statistics of the emission strength in function of emitter loudness. Skewness and kurtosis are identical because the scaling was done after the Monte Carlo simulation. The top one-permille emission (99.9%) of a person breathing quietly is similar to what we reported in our earlier simulation as the upper range of a breathing emitter (Riediker and Tsai, 2020).

We applied the indoor scenario simulator to indoor workplaces such as offices, transport, walk-in businesses and documented superspreading events. We tested the effects of the parameters that often differ in these situations, namely time spent in the room, mask wearing,

Fig. 1. Input distributions used to run the Monte Carlo simulation and resulting distribution of the infected population's viral emission strength while speaking quietly. A: Density plot of the viral load in the population; B: Median size-distribution of aerosol emissions; C: Density plot of the variability of aerosol emissions in the population relative to the median (delogarithmized for visualization purposes); D: density plot of the resulting viral emission strength scaled to speaking quietly.

Table 2. Statistics of viral emission strength distribution obtained from the Monte Carlo simulation for breathing only, speaking quietly, and speaking loudly. ^(a) Percentiles with names were used in the indoor scenario simulator with the corresponding emitter type name.

Statistics	Breathing [copies cm ⁻³]	Speaking quietly [copies cm ⁻³]	Speaking loudly [copies cm ⁻³]
Mean	4.35E-03	4.25E-02	4.25E-01
Standard deviation	5.19E-02	5.07E-01	5.07E+00
Variance	2.69E-03	2.57E-01	2.57E+01
Skewness	3.60E+01	3.60E+01	3.60E+01
Kurtosis	1.90E+03	1.90E+03	1.90E+03
1%	2.04E-09	1.99E-08	1.99E-07
5%	5.50E-09	5.37E-08	5.37E-07
Low 10% ^(a)	1.09E-08	1.06E-07	1.06E-06
25%	7.40E-08	7.23E-07	7.23E-06
Normal 50% ^(a)	1.14E-06	1.11E-05	1.11E-04
75%	6.62E-05	6.47E-04	6.47E-03
High 90% ^(a)	1.96E-03	1.91E-02	1.91E-01
95%	8.22E-03	8.02E-02	8.02E-01
Very high 99% ^(a)	7.96E-02	7.77E-01	7.77E+00
Super 99.9% ^(a)	6.31E-01	6.16E+00	6.16E+01
99.99%	2.12E+00	2.07E+01	2.07E+02

room size, and ventilation rates. Activity and speaking were set to "resting" (sitting, standing) and "quiet" (not making sounds) unless otherwise mentioned. The average wind speed in the room (used to calculate the interzonal near-field flow) was always set at 0.1 m s⁻¹.

3.2 Office Scenarios: Focus on Room Parameters, Emitter Strength, Mask Types and Time in Room

A series of cases in indoor workplaces such as offices were modeled (Table 3) to understand the influence of room parameters (volume), ventilation (AER), emitter strength, wearing mask and mask type, time spent in the room, and speaking. The simulation of a small office shows that for a scenario with a normal emitter (one emitting median virus quantities) spending a few hours in the room, virus levels in the room (far-field) and also in the near-field remain very low, resulting in a dose of 0.02 copies. However, already for high emitters (90%), cumulative inhaled doses can reach the range of hundreds to thousands inhaled virus copies in situations with poor ventilation (around 0.1 per hour AER) and the emitter talking loudly over a longer time period. It thus reaches a range that seems to be critical for viral infections (Sampath *et al.*, 2005; Watanabe *et al.*, 2010; Yezli and Otter, 2011; Karimzadeh *et al.*, 2020; Schröder, 2020). In rooms with very high AER (e.g., open windows all the time), or in large rooms such as open-space offices with standard ventilation rates, concentrations are relatively low as long as the high or very high emitter does not talk loudly nor continuously. The presence of a super-emitter in a meeting room talking frequently or even giving a speech was simulated to result in considerably high doses. If we simulated the same scenario with everyone in the room wearing a surgical mask, the scenario still showed elevated doses.

3.3 Scenarios for Businesses with Walk-in Customers

We next looked at the situation of small businesses with walk-in customers such as small boutiques or repair shops, fine dining restaurants and discos (Table 4). If a super-emitting client entered a shop for 30 minutes, the resulting inhaled dose of the shop staff would be only slightly below the critical dose of 500 inhaled viruses. However, if all wore masks the levels would be well below the critical dose. In contrast, a client may inhale a critical dose if visiting late in the day a shop with the staff being a super-emitter not wearing a mask as the client would be exposed to a concentration above 2,000 viruses m⁻³. This exposure was markedly reduced had the staff worn a mask.

Table 3. Office situations assessed with the indoor scenario simulator (**Bold:** inhaled dose > 500 copies).

Scenario	Room size [m ³]	Air exchange rate [h ⁻¹]	Final room concentration [copies m ⁻³]	Cumulative dose, person in room [copies]	Final near-field concentration [copies m ⁻³]	Cumulative dose, person in near-field [copies]
4 hours in small room, different types of emitter and talk, moderate ventilation						
normal emitter, 5% talk, no masks	50	1	0.01	0.01	0.01	0.02
high emitter, 5% talk, no masks	50	1	16	24	17	27
very high emitter, 5% talk, no masks	50	1	631	966	694	1,080
super-emitter, 5% talk, no masks	50	1	5,005	7,659	5,507	8,562
high emitter, 50% talk, no masks	50	1	58	89	64	99
high emitter, 50% loud, no masks, poor ventilation	50	0.1	1,126	1,453	1,179	1,549
very high emitter, 50% talk, no masks	50	1	2,362	3,615	2,599	4,041
super-emitter, 50% talk, no masks	50	1	18,731	28,666	20,609	32,046
super-emitter, 5% talk, all surgical masks	50	1	1,251	479	1,376	536
super-emitter, 50% talk, all surgical masks	50	1	4,683	1,792	5,152	2,003
4 hours in same small room but with all windows open						
very high emitter, 5% talk, no masks	50	20	50	89	113	203
super-emitter, 5% talk, no masks	50	20	396	706	898	1,609
super-emitter, 5% talk, all surgical masks	50	20	99	44	224	101
4 hours in open space office, moderate ventilation						
very high emitter, 5% talk, no masks	1000	1	32	48	95	162
super-emitter, 5% talk, no masks	1000	1	250	383	752	1,286
super-emitter, 5% talk, all surgical masks	1000	1	63	24	188	80
2 hours in meeting room, size for 10 people, good ventilation						
super-emitter, 10% talk, no masks	100	3	1,467	1,145	2,122	1,734
super-emitter, 10% talk, all surgical masks	100	3	367	72	530	108
super-emitter giving speech, 50% talk, 5% loud, no masks	100	3	7,988	6,234	11,552	9,441
super-emitter giving same speech, all surgical masks	100	3	1,997	390	2,888	590

The simulation of a fine dining restaurant (sitting down and staying for 1 hour) suggests that in places with moderate ventilation (AER: 1 per hour), inhaled doses can become critical. However, if the restaurant is very well ventilated (AER: 10 per hour), levels were below relevant exposures when assuming little talking at low voice. Wearing masks by asymptomatic infected staff will limit relevant exposure of clients. Also in the inverse situation, when the client is infected, the staff would profit from wearing a surgical mask because this resulted already in a relevant difference in estimated inhaled dose. Finally, the simulation of a disco with a dancing and shouting super-emitter suggests a very high risk of infection for everyone in the room. Everyone would need to wear good quality respirators (FFP2 or better) to not inhale critical doses, even when they did not increase their respiration by dancing.

3.4 Transport Scenarios: Travel by Train, Bus, Car, and Air

We also simulated different transport situations (Table 5). In all transport types, super-emitters were predicted to cause high viral exposures especially when talking. In most cases, wearing surgical masks reduced the dose to levels that were below 500 inhaled viral copies. For similar transport distances, taking the train was better than taking a bus, while carpooling was worst. In a simulation of a long-distance bus ride of a group of sports fans or a choir with the emitter shouting or singing loudly during 20% of the travel time, not even surgical masks provided sufficient protection. For carpooling passengers or travelers in a taxi, the simulation showed that strong ventilation alone was not sufficient to reduce the exposure below presumably less critical

Table 4. Situation in walk-in businesses such as small shops, boutiques, restaurants and discos (Bold: inhaled dose > 500 copies).

Scenario	Room size [m ³]	Air Exchange rate [h ⁻¹]	Final room concentration [copies m ⁻³]	Cumulative dose, person in room [copies]	Final near-field concentration [copies m ⁻³]	Cumulative dose, person in near-field [copies]
<i>Small shop / boutique, comparison of situation for client (short stay) and staff (long stay)</i>						
30 minutes, super-emitter, 20% talk, no masks	100	3	1,804	268	2,764	484
30 minutes, super-emitter, 20% talk, all surgical masks	100	3	451	17	691	30
4 hours, super-emitter, 20% talk, no masks	100	3	2,154	3,619	3,115	5,347
4 hours, super-emitter, 20% talk, all surgical masks	100	3	539	226	779	334
<i>Fine dining restaurant, different ventilation settings, staff with/without mask</i>						
2 hours, super-emitter, 20% talk, no masks	500	1	923	612	1,883	1,477
2 hours, super-emitter, 20% talk, no masks	500	10	147	127	1,108	991
2 hours, super-emitter, 20% talk, emitter only surgical mask	500	1	231	153	471	369
2 hours, super-emitter, 20% talk, receiver only surgical mask	500	1	923	153	1,883	369
<i>Disco attended 2 hours by super-emitter, 20% shouting loudly, 50% heavy dancing, no mask. Situation for co-dancers and resting persons with different mask settings</i>						
co-dancers: moderate dancing, no masks	300	3	9,730	15,186	22,752	38,625
resting persons: standing, no masks	300	3	9,730	7,593	22,752	19,313
resting persons: standing, receiver only surgical mask	300	3	9,730	1,898	22,752	4,828
resting persons: standing, receiver only FFP2	300	3	9,730	379	22,752	966

levels, especially when the emitter was in the near-field of other passengers. The simulation of an intercontinental flight suggested that wearing masks kept the inhaled dose at low levels despite the long travel duration and intermittent talking by the emitter. Overall, these scenarios suggest that in transport situations, masks should be worn, and prolonged or loud speaking avoided, especially if the vehicle is small and the travel duration long.

3.5 Reproduction of Super-spreading Events Described in the Literature

We finally aimed to reproduce a number of documented super-spreading events (Table 6). Even when assuming a rather high AER of 3 exchanges per hour, the presence of a super-emitter not wearing a mask would always result in very high airborne virus concentrations. In the case of the fitness dance class in Chenoan, South-Korea (Jang *et al.*, 2020) already a high emitter (90th percentile) would have been sufficient to lead to an inhaled dose of the exposed dancers above 1,000 virus copies. For all these events, the airborne route would be a very plausible explanation if the virus carrier had been a super-emitter.

We also simulated the case of two hair stylists who serviced clients until they were tested positive (Hendrix *et al.*, 2020). Both wore masks and no clients were infected. The clients were reported to have spent on average 15 minutes in the shop. We first assumed a worst case of two super-emitters in a small space with moderate ventilation. Not wearing a mask would lead to a cumulative inhaled dose of a few hundred viruses in the first client, while later clients would inhale several thousand viruses during the 15 minutes in the shop. The hair stylists wearing a surgical mask would keep the cumulative dose of the first client below 100 viruses while later clients would have gotten a dose of a few hundred viruses. However, if both stylists were median emitters, the airborne route would be very low and likely would contribute very little to the overall transmission risk even if neither wore a mask. Since we don't know the viral emitter strength of the stylists, it remains unclear whether the mask protected the customers from directly sprayed large droplets or from virus-loaded aerosols that had accumulated over time (Chu *et al.*, 2020; Riediker, 2020).

Table 5. Situations in transportation when travelling by train, bus, car and air (Bold: inhaled dose > 500 copies).

Scenario	Room size [m ³]	Air Exchange rate [h ⁻¹]	Final room concentration [copies m ⁻³]	Cumulative dose, person in room [copies]	Final near-field concentration [copies m ⁻³]	Cumulative dose, person in near-field [copies]
Travelling by train, commute or long distance						
60 minutes, super-emitter, quiet, no masks	57	7.1	644	255	993	412
60 minutes, super-emitter, 20% talk, no masks	57	7.1	1,774	702	2,734	1,134
60 minutes, super-emitter, 20% talk, all surgical masks	57	7.1	444	44	684	71
3 hours, super-emitter, quiet, no masks	160	9.4	177	232	526	703
3 hours, super-emitter, 20% talk, no masks	160	9.4	487	638	1,448	1,934
3 hours, super-emitter, 20% talk, all surgical masks	160	9.4	122	40	362	121
Trolleybus ride, 30 minutes with frequent stops						
doors open each stop, super-emitter, 20% talk, no masks	100	10	732	137	1692	353
doors rarely open, super-emitter, 20% talk, no masks	100	2	2,175	305	3,136	521
doors rarely open, super-emitter, 20% talk, all surgical masks	100	2	544	19	784	33
Regular long-distance bus ride, doors rarely open						
90 minutes, super emitter, 20% talk, no masks	50	2	5,831	3,038	6,792	3,686
90 minutes, super emitter 20% talk, all surgical masks	50	2	1,457	189	1,698	237
Sport fans or choir in long-distance bus, increased ventilation						
3 hours, super-emitter, 50% loud, no masks	50	5	49,775	63,401	66,982	86,630
3 hours, super-emitter, 50% loud, all surgical masks	50	5	12,444	3,963	16,745	5,414
Taxi or carpool, using mid-size (large family) car						
30 minutes, super-emitter, recirculation, 10% talk, no masks	3.3	10	15,120	2,834	15,775	2,981
30 minutes, super-emitter, all fresh air, 10% talk, no masks	3.3	40	3,976	864	4,630	1,011
30 minutes, super-emitter, recirculation, 10% talk, all surgical masks	3.3	10	3,780	177	3,943	186
Mini-Bus, people mover						
30 minutes, super-emitter, 20% talk, no masks	20	5	6,529	1,064	7,409	1,250
30 minutes, super-emitter, 20% talk, all surgical masks	20	5	1,632	66	1,072	80
Intercontinental flight						
10 hours, super-emitter, 10% talk, no masks	700	10	72	320	726	3,265
10 hours, super-emitter, 10% talk, all surgical masks	700	10	18	20	182	204

3.6 Discussion of the Method and Tool, Use and Limitations

In our study, we developed an indoor scenario simulator that allows altering room volume, AER, type of virus spreader, physical activity, loudness of speech, wearing masks, type of mask and time spent in the indoor environment. Temperature, ultraviolet light intensity and humidity are not included because they were found to modify the half-life of SARS-CoV-2 only at conditions that are rarely present in indoor environments (Schuit *et al.*, 2020). We applied the tool to a number of scenarios to show how different factors influence the predicted concentration and dose of virus copies in the room air and the near-field of an emitting person (within 0.6 m).

Table 6. Reproduction of documented super-spreading events (Bold: inhaled dose > 500 copies).

Scenario (emitter set to highest type leading to cumulative dose in far-field > 1,000)	Room size [m ³]	Air Exchange rate [h ⁻¹]	Final room concentration [copies m ⁻³]	Cumulative dose, person in room [copies]	Final near-field concentration [copies m ⁻³]	Cumulative dose, person in near-field [copies]
Restaurant in Guangzhou , CN (Lu <i>et al.</i> , 2020) 60 minutes, super-emitter 20% loud, no masks	450	3	3,442	1,177	10,534	4,369
Medical board meeting in Munich , DE (Hijnen <i>et al.</i> , 2020) 9.5 hours, super-emitter 10% talk, no masks	210	3	699	2,905	1,354	5,703
Call Center in Seoul , KR (Park <i>et al.</i> , 2020) 4 hours, very high emitter 75% loud, no masks (estimate for one half-day of work, real case: several days)	1,000	3	725	1,218	3,957	7,037
Choir rehearsal in Skagit Valley , US (Hamner <i>et al.</i> , 2020) 3 hours, super-emitter sings 50% loud, no masks (simplified, assumes full rehearsal in one large room)	1,000	3	4,203	5,168	22,939	30,462
Fitness dance class in Chenoan , KR (Jang <i>et al.</i> , 2020). 50 mins, high emitter 50% loud, all 100% heavy exercise, no masks	100	3	684	1,123	1,003	1,843
Hair stylist in Springfield (a) , US (Hendrix <i>et al.</i> , 2020) client enters 1 hour after stylists, stays 15 mins, two super-emitters 10% light exercise and 20% talk, all surgical masks (second line: exposure and dose without masks)	50	1	4,589 (18,357)	305 (1,384)	4,853 (19,414)	335 (2,117)
Hair stylist in Springfield (b) , US (Hendrix <i>et al.</i> , 2020) same as above but both stylists entered as normal emitters	50	1	0.01 (0.03)	<0.01 (< 0.01)	0.01 (0.03)	< 0.01 (< 0.01)

Decision makers, ventilation and occupational planners, occupational and public health experts, and other specialists can use this simulation tool to investigate their own indoor environment settings and scenarios. The critical dose, the number of viruses determined by PCR above which there seems to be an increased potential of infection, is subject to ongoing research and may be lower for vulnerable groups. It can therefore be easily adapted in the tool. In our simulator, the default of the critical dose was set to 500 inhaled viral copies because this seemed likely a level of low risk of infection for a healthy population as discussed in the introduction. However, for sensitive populations, lower levels seem advisable. The simulator allows to easily adjust the critical dose. It also provides the minimal contact time for reaching a given critical dose, which can be helpful to define a "safe time" in a room but also to study the importance of the time-dose metric for COVID-19 infections (Pujol *et al.*, 2009).

However, there are some limitations. First, the tool is based on a simple mass balance near-field far-field model and its assumptions, such as well mixing of the airborne virus in the space. Second, sedimentation of aerosols was approximated by using the PM₁₀ fraction of the emitted aerosols because calculating a real sedimentation term would require information on local airstreams and geometry. For short durations, this can underestimate the exposure because not all large aerosol will sediment immediately, while for longer durations, the influence of sedimentation may be underestimated. Thus, for critical scenarios, it would be advisable to use simulations with test aerosols or computational fluid dynamics approaches that assess the fate of all emitted particle sizes including the very large ones, and that takes into account inhomogeneous mixing of the air in a room. A third limitation is that aerosol data gained from healthy young people was used to calculate the emission strength. It is likely that the infection with SARS-CoV-2 causes changes in the aerosol size distribution, but it is not certain that this will be similar to what is known for upper respiratory tract diseases (Lee *et al.*, 2019), given that asymptomatic individuals infected with the SARS-CoV-2 virus do not report typical upper respiratory tract disease symptoms. Fourth, the scenario-builder simplifies viral emissions by defining only one category of emitter-strength, even though high aerosol formation for breathing and talking were reported to not necessarily go together (Asadi *et al.*, 2019). Fifth, the tool provides the number of viral copies determined by RNA testing (Jones *et al.*, 2020), but for SARS-CoV-2 it is not yet known how RNA-copies measured in human liquids relate to infective, plaque-forming virus units (PFU). Finally, only transmission by aerosols is assessed. This has to be kept in mind in particular when looking at the near-field where spray-processes emitting large droplets are likely to lead to much higher virus exposures.

The here developed indoor scenario simulator allows assessing different factors influencing the airborne exposure to SARS-CoV-2 in a variety of indoor settings. The dose in many of the scenarios was below 500 virus copies, which seems to be a low risk for infection, as discussed earlier (Watanabe *et al.*, 2010; Yezli and Otter, 2011; Karimzadeh *et al.*, 2020; Sampath *et al.*, 2005; Schröder, 2020). We also assessed the tool in comparison to documented super-spreading events. Our simulations suggest that these infective events could be explained by the airborne route and that an estimated dose of a few thousand virus copies may be sufficient to infect a large proportion of exposed people.

The risk of transmission and infection from exposure depends not only on the viral dose, but also on individual factors such as age, individual susceptibility, preexisting medical conditions and the correct use of protective measures. The airborne route is not the only way one can get infected with the virus, as seen by the effectiveness of hand washing, keeping distance and protecting the eyes when in close distance. We therefore opted against the calculation of a "quantum risk" (Buonanno *et al.*, 2020) but prefer to simply report the estimated viral exposure levels and inhaled doses.

4 CONCLUSIONS

The here developed indoor scenario simulator allows estimating the viral exposure and inhaled dose in different indoor settings, based on a simulation of droplet generation and assumptions of indoor conditions. It was created to allow decision makers as well as workplace and facility experts to assess and improve their protection concepts, and to guide indoor exposure

assessment campaigns. The tested scenarios document the positive effects of wearing masks and ventilation, and the contribution of viral load, speaking and physical activity. The parameter driving the risk is in most scenarios the emission rate of the infected person: the presence of a super-emitter (99.9%) or very high emitter (99%) was required to reach a critical number of inhaled copies. In very small rooms with poor ventilation (e.g., sitting in a car), already a high emitter (90%) was sufficient, especially if the emitter was singing or talking loudly. Wearing simple surgical/hygiene masks was very effective in almost all cases. However, the retention rate of the different masks is based on the assumption of fit and proper wear by the infected emitters. Personal observation in public spaces suggests that this does not always hold, which has to be considered when doing risk assessments for populations that have difficulties following guidelines and rules.

The analysis of documented super spreading events suggests that the application of the simulator may be useful to predict worst-case scenarios. Preventive efforts should aim at preventing situations where people gather unprotected in small airspaces because in such situations, the presence of a single super-emitter can rapidly result in a super-spreading event. In such situations, mask should be worn, and people should be asked to remain quiet.

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DISCLAIMER

The contents of this article do not necessarily represent SECO policy, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <https://doi.org/10.4209/aaqr.2020.08.0531>

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