Superspreading events suggest aerosol transmission of SARS-CoV-2 by accumulation in enclosed spaces

John M. Kolinski, Tobias M. Schneider

1 Institute of Mechanical Engineering, École Polytechnique Fédérale de Lausanne
Lausanne, 1015, Switzerland
*To whom correspondence should be addressed; E-mail: john.kolinski@epfl.ch
or tobias.schneider@epfl.ch.

Viral transmission pathways have profound implications for public safety. Mounting evidence suggests SARS-CoV-2 can be transmitted via the air; however, this has not yet been demonstrated. Here we quantitative analyze virion accumulation by accounting for aerosolized virion emission and destabilization. Reported superspreading events analyzed within this framework point towards aerosol mediated transmission of SARS-CoV-2. For 20 independent events, the computed virion exposure count falls in a narrow range, suggesting a universal minimum infective dose (MID) via aerosol that is comparable to the MIDs measured for other respiratory viruses.

The infectious pathways of a virus determine its course through a host population. Whether a virus is transmitted is governed by the virus shedding rate of an infected host, the minimal infective dose (MID) required to infect, and the transmission pathway. Despite clear guidelines on social distancing and lock-down policies intended to disrupt transmission of SARS-CoV-2 by respiratory droplet transmission (1), containment of SARS-CoV-2 has proven to be a challenging due in part to its prolonged symptomless incubation period (2, 3). Ongoing developments
of the guidance regarding possible aerosol transmission reflect uncertainty about the role of aerosols in viral transmission; indeed, mask-wearing is marginally effective in reducing viral transmission (4), but not all infectious particles are captured by typical surgical masks (5), complicating a direct assessment of the role of aerosols in transmitting SARS-CoV-2. While there is some evidence for the aerosol transmission of the virus (6, 7), the circumstances under which aerosol transmission might be expected are currently unknown.

Here we quantitatively analyze several reported superspreading events (8–13) involving over 200 infected persons and over 1000 exposed persons, and find that aerosol mediated transmission of SARS-CoV-2 is likely the infective pathway. In these 20 recent superspreading events, the primary source of the infection was not likely have been in near- or intinite contact with the infected group. Each of these events took place in an enclosed environment, and the time duration of exposure and room volume are either reported or estimated as described in the supplementary material.

The aerosolized virus emitted by an infected person in an enclosed space will accumulate until virion emission and virion destabilization are balanced, resulting in a steady-state concentration $C_\infty$. The accumulation timescale results in a significantly enhanced exposure when virus-carrying aerosol droplets are inhaled for longer duration co-occupancy. The superspreading events analyzed in this framework are found to trace out a single value of the calculated virion exposure, suggesting a universal minimum infective dose (MID) via aerosol for SARS-CoV-2. The MID implied by our analysis is comparable to the measured MIDs for influenza A (H2N2) (14, 15), the virus responsible for the 1957-1958 Asian flu pandemic. Our model suggests that infection via aerosol is less likely with a filtration rate exceeding the destabilization rate of aerosolized SARS-CoV-2.

The pathway for transmission of respiratory viruses via droplets depends on their size, as depicted schematically in Fig. 1 A. Small droplets with diameter 2a below 5 microns settle in
quiescent air at a velocity set by the balance of the gravitational force $F_g = 4/3 \pi \rho g a^3$ and
the Stokes drag force, $F_d = 6\pi a \mu v$. Such a droplet descends at a velocity $v$ of 2.5 m/hour;
however, prevailing currents in a typical room significantly exceed this settling velocity. Thus,
aerosolized droplets will remain suspended for hours, and disperse widely in an occupied room
within minutes (6, 7). Due to this rapid and thorough mixing of aerosols, the physical dis-
tance between persons in an enclosed space becomes irrelevant; exposure to the airborne virus
is controlled only by the virus concentration. This is in contrast to large respiratory droplet
transmission, as these droplets fall to the ground in seconds, limiting the spatial range of infect-
tivity (1, 16–18).

Motivated by these considerations of droplet suspension velocity, we assume that the flow
within the room under consideration is well-mixed within minutes; this is fast compared to
the aerosolized SARS-CoV-2 destabilization rate $\gamma$, which is 1/hour for SARS-CoV-2 (19).
Because the air is well mixed, the complex spatio-temporal evolution of aerosol distribution
can be represented by the uniform virion concentration $C(t)$, which is a function of time only.

To study the effect of virus accumulation in closed and unfiltered environments, we use
straightforward conservation laws of aerosol-born virions to formulate an expression for the
evolution of the volumetric concentration of aerosolized virions $C(t)$ at time $t$ in terms of a
viral source $s$, in number of aerosol-born viral particles shed per time, and the destabilization
rate $\gamma$, as $\frac{dC(t)}{dt} = s/V - \gamma C(t)$. Here $V$ is the room volume. The solution $C(t) = \frac{s}{\gamma V} (1 - e^{-\gamma t})$
describes the temporal evolution of $C$, as shown in Fig. 1 B. If the room air is filtered or replen-
ished, a third term $\gamma_{\text{filt}} C(t)$ is subtracted from the right-hand side of this equation yielding an
effective destabilization rate that combines the natural decay and filtration, as presented in Fig.
S1.

While the viral shedding rate for SARS-CoV-2 has not yet been measured, the average virion
sheding rate for other coronaviruses was measured at $s = 32,600$ virions / hour. We use this
value for $s$ throughout this study, as described in the supplementary materials. We can now calculate the steady-state concentration of virions $C_{\infty}$ for an infectious person in a room of a given size. A single infected person shedding aerosolized virus in a large room of 300 cubic meters yields $C_{\infty} = 109$ virions/m$^3$, while in a smaller space of 40 cubic meters gives a much larger $C_{\infty} = 814$ virions/m$^3$. This steady-state concentration is reached after a transient period given by the inverse destabilization rate of the virus; since $\gamma$ is 1/hour, short-term occupancy is unlikely to reach the steady-state concentration, significantly reducing virion exposure in transient encounters.

Is an occupant likely to be infected at such concentrations? To answer this question, we calculate the virion exposure $N_{\text{exp}}$, recognizing that it must exceed a minimum infective dose (MID), which remains unknown for SARS-CoV-2. $N_{\text{exp}}$ is given by the time-integral of the respiration rate of a room occupant, $\dot{Q}$, as $N_{\text{exp}} = \int_{0}^{T} C(t)\dot{Q} dt$, where $\dot{Q}$ is the respiration rate. The average adult at rest takes 12 breaths per minute, cycling a volume of 0.5 liters / breath; this amounts to a total respiration rate of 360 liters per hour, or $\dot{Q} = 0.36m^3$ / hour. Thus, $N_{\text{exp}}$ in the above cases is 14 and 108 per hour, respectively. For $T = 30$ min, $N_{\text{exp}} = 4$ and 31 particles, respectively as $C < C_{\infty}$.

Expanding this analysis to arbitrary $T$ and $V$, we calculate several iso-$N_{\text{exp}}$ curves, plotted in Fig. 2. At room volumes that are typically encountered in daily activities, and over timescales of co-occupancy of the order of hours, we observe iso-$N_{\text{exp}}$ values that fall within the range of the MIDs reported for other aerosol-transmissible viruses including the aggressive Influenza A (H2N2), adenoviruses and SARS-CoV-1 (14, 15, 20), pointing to the possibility of aerosolized transmission of SARS-CoV-2.

To assess the viability of aerosolized SARS-CoV-2 transmission despite its unknown MID, we analyse reported superspreading events (8–13) that comply with our analytical framework, and either directly report or offer a means of reasonably estimating the room volume $V$ and
co-occupancy time $T$, as described in the supplementary material.

The $V$ and $T$ values for the events involving a single viral shedder at resting $\dot{Q}$ are directly compared with the calculated iso-$N_{exp}$ values plotted in Fig. 2. For these five events, the data consistently fall between $N_{exp} = 50$ and 100; the tight range of $N_{exp}$ values emerging from this analysis suggests a possible unique MID via aerosol transmission for SARS-CoV-2 of $N_{exp} \approx 50$.

If the value of $N_{exp} \approx 50$ is indeed the MID for aerosol transmission of SARS-CoV-2, it should independently arise under further analysis. We test this hypothesis by evaluating additional super-spreading events with identical co-occupancy, but different respiration rates (9) or number of spreaders (10). Accounting for modifications of $s$ or $\dot{Q}$ as described in the supplementary materials, we tabulate and graph the predictions of $N_{exp}$, including the data from Figure 2; altogether, this analysis includes over 200 infections and over 1000 exposed persons. We find that all cases fall within the anticipated range of $N_{exp} \approx 50$ virions with the exception of two events that involve documented close physical contact (10, 13), as shown in Fig. 3. This suggests a robust MID for SARS-CoV-2 via aerosol transmission.

Our model incorporates two key parameters: first, the rate of aerosolized virions shed by an infected person $s$, inferred from data for other coronaviruses (21) as described in the supplementary material, and second, the virion destabilization rate $\gamma$, measured for SARS-CoV-2 (19). We additionally assume that filtration is slow compared to the viral destabilization rate. However, this framework can account for filtration, as we present in detail in Fig. S1. In hospital environments, where the air filtration rate can exceed 10 volumes per hour, our model suggests that $N_{exp}$ over several hours can be reduced approximately 10-fold. Such a reduction would potentially reduce $N_{exp}$ below the MID for SARS-CoV-2, and might explain why exposed medical workers in a hospital environment were not infected (22, 23).

Within the framework of aerosol transmission by accumulation, superspreading events sug-
gest a MID for SARS-CoV-2 commensurate with other infectious viruses, including the influenza-A (H2N2) strand that caused the 1957-'58 influenza pandemic (14, 15). Indeed, our study suggests that in terms the MID for aerosol transmission, SARS-CoV-2 behaves much like a particular flu - unfortunately, the H2N2 flu strand that generated a global pandemic.

Under the condition that virions are transported by aerosol droplets, data from several reported superspreading events all indicate the same narrow range of infectious dose. This corroborates the emerging scientific consensus (6, 7, 24), and points towards the practical relevance of aerosol transmission of SARS-CoV-2

References

1. Advice for the public on COVID-19 World Health Organization. https://www.who.int/emergencies/diseases/novel-coronavirus-2019/advice-for-public (2020).

2. H. Chu, et al., Comparative Replication and Immune Activation Profiles of SARS-CoV-2 and SARS-CoV in Human Lungs: An Ex Vivo Study With Implications for the Pathogenesis of COVID-19, Clin. Infect. Dis. https://academic.oup.com/cid/advance-article/doi/10.1093/cid/ciaa410/5818134 (2020).

3. N. W. Furukawa, J. T. Brooks, J. Sobel, Evidence Supporting Transmission of Severe Acute Respiratory Syndrome Coronavirus 2 While Presymptomatic or Asymptomatic, Emerg. Infect. Dis. 26 (2020). http://wwwnc.cdc.gov/eid/article/26/7/20-1595_article.htm (2020).

4. R. Zhang, Y. Li, A. L. Zhang, Y. Wang, M. J. Molina, Identifying airborne transmission as the dominant route for the spread of COVID-19, Proc. Natl. Acad. Sci. USA 117, 14857 (2020).
5. C. J. Khler, R. Hain, Fundamental protective mechanisms of face masks against droplet infections, *J. Aerosol Sci.* **148**, 105617 (2020).

6. L. Morawska, J. Cao, Airborne transmission of SARS-CoV-2: The world should face the reality, *Environ. Int.* **139**, 105730 (2020).

7. K. A. Prather, C. C. Wang, R. T. Schooley, Reducing transmission of SARS-CoV-2, *Science* **368**, 1422 (2020).

8. L. Hamner, et al., High SARS-CoV-2 Attack Rate Following Exposure at a Choir Practice Skagit County, Washington, March 2020, *MMWR-Morbid. Mortal. W. 69*, 606 (2020).

9. S. Jang, S. H. Han, J.-Y. Rhee, Cluster of Coronavirus Disease Associated with Fitness Dance Classes, South Korea, *Emerg. Infect. Dis.* **26**, 1917 (2020).

10. R. Pung, et al., Investigation of three clusters of COVID-19 in Singapore: implications for surveillance and response measures, *Lancet* **395**, 1039 (2020).

11. J. Lu, et al., COVID-19 Outbreak Associated with Air Conditioning in Restaurant, Guangzhou, China, 2020, *Emerg. Infect. Dis.* **26**, 1628 (2020).

12. T. Gnther, et al., Investigation of a superspreading event preceding the largest meat processing Preprint at https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3654517 (2020).

13. D. Yusef, et al., Large Outbreak of Coronavirus Disease among Wedding Attendees, Jordan, *Emerg. Infect. Dis.* **26**, https://wwwnc.cdc.gov/eid/article/26/9/20-1469_article (2020).

14. S. Yezli, J. A. Otter, Minimum Infective Dose of the Major Human Respiratory and Enteric Viruses Transmitted Through Food and the Environment, *Food Environ. Virol.* **3**, 1 (2011).
15. I. Schrder, COVID-19: A Risk Assessment Perspective, ACS Chem. Health Saf. 27, 160 (2020).

16. L. Bourouiba, Turbulent Gas Clouds and Respiratory Pathogen Emissions: Potential Implications for Reducing Transmission of COVID-19, JAMA 323 (2020).

17. R. Mittal, R. Ni, J.-H. Seo, The flow physics of COVID-19, J. Fluid Mech. 894, F2 1 (2020).

18. G. A. Somsen, C. van Rijn, S. Kooij, R. A. Bem, D. Bonn, Small droplet aerosols in poorly ventilated spaces and SARS-CoV-2 transmission, Lancet Resp. Med. 8, 658 (2020).

19. N. van Doremalen, et al., Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1, New Engl. J. Med. 382, 1564 (2020).

20. T. Watanabe, T. A. Bartrand, M. H. Weir, T. Omura, C. N. Haas, Development of a Dose-Response Model for SARS Coronavirus, Risk Anal. 30 (2010).

21. N. H. L. Leung, et al., Respiratory virus shedding in exhaled breath and efficacy of face masks, Nat. Med. 26, 676 (2020).

22. S. Faridi, et al., A field indoor air measurement of SARS-CoV-2 in the patient rooms of the largest hospital in Iran, Sci. Total Environ. 725, 138401 (2020).

23. V. C.-C. Cheng, et al., Air and environmental sampling for SARS-CoV-2 around hospitalized patients with coronavirus disease 2019 (COVID-19), Infect. Control Hosp. Epidemiol. pp. 1–8. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7327164/ (2020).

24. K. P. Fennelly, Particle sizes of infectious aerosols: implications for infection control, Lancet Resp. Med. https://linkinghub.elsevier.com/retrieve/pii/s2213260020303234 (2020).
Supplementary materials

Methods

Fig. S1
Figure 1: Aerosolization of viral cargo in an enclosed space. (A) A schematic of a closed room with volume $V$. An infected person can emit both rapidly sedimenting respiratory droplets and aerosol-sized particles. Particles with a diameter of 5 µm sediment in quiescent air at a rate of 3 m/hour. These particles are readily dispersed by air currents. (B) For aerosolized virus emitted into an enclosed space, the rate of emission will ultimately be balanced by the destabilization rate; these dynamics lead to the evolution of aerosolized virus concentration plotted here. A non-infected occupant breathing at a constant rate in the same space is exposed to $N_{exp}$ particles over time (right axis).
Figure 2: Curves of constant aerosolized virion exposure for a fixed source strength and breathing rate. $N_{\text{exp}}$, the number of viral particles a room occupant is exposed to, is calculated as a function of room volume $V$ and occupancy time $T$, as indicated on each curve. Data from several superspreading events (8, 10–12) with a single spreading source at the resting respiratory rate are plotted on the graph, with error bars indicated for the events. Details of these data, and of the calculation of the iso-$N_{\text{exp}}$ curves, are included in the supplementary material.
Figure 3: Tabulated data for several superspreading events. A total of 20 distinct superspreading events (5–13) for SARS-CoV-2 are analyzed, and the parameter values used to formulate the prediction for numerical value of viral particle exposure $N_{exp}$. The predicted value for $N_{exp}$ is plotted on the graph at the right with a red diamond; the range of predicted values are shown with blue rectangles. Details of these data ranges are included in the supplementary material.

| Event description       | $\dot{Q}$ (m$^3$/hr) | $V$ (m$^3$) | $T$ (hr) | $N_{pred}$ |
|-------------------------|-----------------------|-------------|----------|------------|
| Choral practice$^{21}$  | 0.36                  | 350 ± 25    | 2.5      |            |
| Fitness classes$^{22,23}$| 1.08                  | 210 ± 30    | 0.83     |            |
| Health store$^{21,24}$  | 0.36                  | 140 ± 60    | 0.5      |            |
| Jewelry store$^{21,23}$ | 0.36                  | 180 ± 60    | 1        |            |
| Conference dinner$^{23}$| 0.36                  | 396 ± 72    | 3        |            |
| Church service$^{23}$   | 0.36                  | 180 ± 60    | 2        |            |
| Restaurant lunch$^{24}$ | 0.36                  | 90 ± 20     | 1.25     |            |
| German meat plant$^{25}$| 0.36                  | 2830 ± 20   | 18       |            |
| Jordanian wedding$^{26,2}$| 0.36              | 2600 ± 700  | 2        |            |

1. The respiratory rate at the fitness class is taken to be three times larger than the resting respiratory rate.
2. The number of infectors is two, and not one for these events.
3. Close personal contact is specifically cited in both of these events.

---

12