# Practical Indicators for Risk of Airborne Transmission in Shared Indoor Environments and their application to COVID-19 Outbreaks

**Z. Peng,[1] W. Bahnfleth,[2] G. Buonanno,[3] S. J. Dancer,[4,5] J. Kurnitski,[6] Y. Li,[7] M.G.L.C. Loomans[8], L.C. Marr,[9] L. Morawska,[10] W. Nazaroff,[11] C. Noakes,[12] X. Querol,[13] C. Sekhar,[14] R. Tellier,[15] T. Greenhalgh,[16] L. Bourouiba,[17] A. Boerstra,[18] J. Tang,[19] S. Miller,[20] and J.L. Jimenez[1*]**

*Affiliations*

1. Dept. of Chemistry and CIRES; University of Colorado, Boulder, CO, USA
2. Dept. of Architectural Engineering, The Pennsylvania State University, University Park, PA, USA
3. Dept. of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, Italy
4. Dept. of Microbiology, NHS Lanarkshire, Scotland, UK
5. School of Applied Sciences, Edinburgh Napier University, Scotland, UK
6. REHVA Technology and Research Committee, Tallinn University of Technology, Tallinn, Estonia
7. Dept. of Mechanical Engineering, the University of Hong Kong, Hong Kong, China
8. Dept. of the Built Environment, Eindhoven University of Technology, Eindhoven, the Netherlands
9. Dept. of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, USA
10. International Laboratory for Air Quality and Health, Queensland University of Technology, Brisbane, Australia
11. Dept. of Civil and Environmental Engineering, University of California, Berkeley, CA, USA
12. School of Civil Engineering, University of Leeds, Leeds, UK
13. Institute of Environmental Assessment and Water Research, IDAEA, Spanish Research Council, CSIC, Barcelona, Spain
14. Dept. of Building, National University of Singapore, Singapore
15. McGill University, Montreal, QC, Canada
16. Dept. of Primary Care Health Sciences, University of Oxford, Oxford, UK.
17. The Fluid Dynamics of Disease Transmission Laboratory, Massachusetts Institute of Technology, Cambridge, MA, USA
18. REHVA (Federation of European Heating, Ventilation and Air Conditioning Associations), BBA Binnenmilieu, the Netherlands
19. Respiratory Sciences, University of Leicester, Leicester, UK
20. Dept. Mechanical Engineering, University of Colorado, Boulder, CO, USA

*: corresponding author: <jose.jimenez@colorado.edu>

**Abstract.** Some infectious diseases, including COVID-19, can be transmitted via aerosols that are emitted by an infectious person and inhaled by susceptible individuals. Although physical distancing effectively reduces short-range airborne transmission, many infections have occurred when sharing room air despite maintaining distancing. We propose two simple parameters as indicators of infection risk for this situation. They combine the key factors that control airborne disease transmission indoors: virus-containing aerosol generation rate, breathing flow rate, masking and its quality, ventilation and air cleaning rates, number of occupants, and duration of exposure. COVID-19 outbreaks show a clear trend in relation to these parameters that is consistent with an airborne infection model, supporting the importance of airborne transmission for these outbreaks. The observed trends of outbreak size vs. risk parameters allow us to recommend values of the parameters to minimize COVID-19 indoor infection risk. All of the pre-pandemic spaces are in a regime where they are highly sensitive to mitigation efforts. Measles outbreaks occur at much lower risk parameter values than COVID-19, while tuberculosis outbreaks are observed at much higher risk parameter values. Since both diseases are accepted as airborne, the fact that COVID-19 is less contagious than measles does not rule out airborne transmission. It is important that future outbreak reports include ventilation information, to allow expanding our knowledge of the circumstances conducive to airborne transmission of different diseases.

**Key words**

COVID-19; airborne transmission; indoor air; risk assessment; mitigation

**Synopsis**

We propose simple parameters of COVID-19 airborne transmission risk and apply them to relevant risk assessment and mitigation.

## Introduction

Some respiratory infections can be transmitted through the airborne pathway, in which aerosol particles (< 100 μm) are shed by infected individuals and inhaled by others, causing disease in susceptible individuals.[1–4] It is widely accepted that measles, tuberculosis, and chickenpox are transmitted in this way,[5,6] and acceptance is growing that this is a major and potentially the dominant transmission mode of COVID-19.[7–13] There is substantial evidence that smallpox,[14] influenza,[3] SARS,[15] MERS,[6] and rhinovirus[16] are or were also transmitted via aerosols.

There are three airborne transmission scenarios of interest in which infectious and susceptible people: (a) are in close proximity to each other (< 1-2 m), so-called “short-range airborne transmission,”[17] which is effectively mitigated by physical distancing; (b) share air in the same room, “shared space airborne”; and (c) “longer-distance airborne transmission” in buildings when individuals are not sharing a room (or are in very large rooms), or even between buildings as in the Amoy Gardens SARS outbreak.[15] Often (b) and (c) are lumped together under “long-range transmission,” but it is useful to separate them given the substantial differences in the risk of these situations and actions needed to abate the risk of transmission.

Airborne diseases vary widely in transmissibility, but all of them are most easily transmitted at short range due to the higher concentration of pathogen-containing aerosols close to the infected person. For SARS-CoV-2, a pathogen of moderate infectivity, many instances have been reported implicating transmission in shared indoor spaces. Indeed, multiple outbreaks of COVID-19 have been reported in crowded spaces that were relatively poorly ventilated and that were shared by many people for periods of half an hour or longer. Examples include choir rehearsals,[11] religious services,[18] buses,[19] workshop rooms,[19] restaurants,[4,20] and gyms,[21] among others. There are only a few documented cases of longer-distance transmission of

SARS-CoV-2, in buildings.[22–24] However, cases of longer-distance transmission are harder to detect as they require contact tracing teams to have sufficient data to connect cases together and rule out infection elsewhere. Historically, it was only possible to prove longer-distance transmission in the complete absence of community transmission (e.g. ref 14).

Being able to quickly assess the risk of infection for a wide variety of indoor environments is of the utmost importance given the impact of the continuing pandemic (and the risk of future pandemics) on so many aspects of life in almost every country of the world. We urgently need to improve safety of the air we breathe across a range of environments including child-care facilities, kindergartens, schools, colleges, shops, offices, homes, eldercare facilities, factories, public and private transportation, restaurants, gyms, libraries, cinemas, concert halls, places of worship and mass outdoor events and across different climates and socio-economic conditions. There is very little evidence on the actual ventilation rates and the effectiveness of ventilation systems at reducing risks from viral exposure and other indoor pollutants within the majority of buildings. However, data from COVID-19 outbreaks consistently shows that multiple buildings worldwide have very low ventilation rates despite the requirements set in national building standards. A host of policy questions – from how to safely re-open schools to how to prevent transmission in high-risk occupational settings – require accurate quantification of the multiple interacting variables that influence airborne infection risk.

Qualitative guidance to reduce the risk of airborne transmission has been published.[25–27] Different mathematical models have been proposed to help manage risk of airborne transmission,[28,29] and several models have been adapted to COVID-19.[30–33] It is important to define quantitative infection risk criteria for different spaces and types of events to more effectively manage the pandemic.[34] Such criteria could then be used by authorities and policy makers to assist in deciding which activities are permitted under what conditions, so as to limit

infection risk across a society. To our knowledge, no such quantitative criteria have been proposed.

Here, we use a box model to estimate the viral aerosol concentration indoors, and combine it with the Wells-Riley infection model.[28] The combined model is used to derive two quantitative risk parameters that allow comparing the relative risk of transmission in different situations when sharing room air. We explore the trends in infections observed in outbreaks of COVID-19 and other diseases as a function of these parameters. Finally, we use the parameters to quantify a graphical display of the relative risk of different situations and mitigation options.

## Materials and Methods

### Box model of infection

The box model considers a single enclosed space, in which virus-containing aerosols are assumed to be rapidly uniformly mixed compared with the time spent by the occupants in the space. This is approximately applicable in many situations, but there are some exceptions such as outbreaks where clear directional flow occurred in a room.[18,20] The mathematical notation used in the paper is summarized in Table S1. The mass balance equation is first written in terms of c, the concentration of infectious quanta in the air in the enclosed space (units of quanta $m^{-3}$). Compared with a model written in terms of aerosol or viral particle concentrations, c has the advantage of implicitly including effects such as the deposition efficiency of the aerosol particles in the lungs of a susceptible person, as well as the efficiency with which such deposited particles may cause infection, the multiplicity of infection (MOI), etc. The balance of quanta in the space can be written as:

$$dc/dt = E_p f_e / V - (\lambda_0 + \lambda_{dec} + \lambda_{dep} + \lambda_{cle}) c \quad (1)$$

where $E_p$ is the emission rate of quanta into the indoor air from an infected person present in the space (quanta / h); $f_e$ is the penetration efficiency of virus-carrying particles through masks or face coverings for exhalation (which takes into account the impact of whether the infector wears a face covering); V is the volume of the space; $\lambda_0$ is the first-order rate of removal of quanta by ventilation with outdoor air ($h^{-1}$); $\lambda_{cle}$ is the removal of quanta by air cleaning devices (e.g. recirculated air with filtering, germicidal UV, portable air cleaners, etc.); $\lambda_{dec}$ is the infectivity decay rate of the virus; $\lambda_{dep}$ is the deposition rate of airborne virus-containing particles onto surfaces. $E_p$ is a critical parameter that depends strongly on the disease, and it can be estimated with a forward model based on aerosol emission rates and pathogen concentration in saliva and respiratory fluid[31,35] or by fitting a model such as the one used here to real transmission events.[11,31]

This equation can be solved analytically or numerically for specific situations. Given the enormous number of possible situations, and given the prevalence of outbreaks resulting from longer events where air is shared for a substantial period of time, we consider a sufficiently long event so that a steady state condition ($dc/dt \sim 0$) is a reasonable approximation. Writing $\lambda = \lambda_0 + \lambda_{cle} + \lambda_{dec} + \lambda_{dep}$ for simplicity leads to a steady-state infectious quanta concentration of:

$$c = E_p f_e / (V \lambda) \quad (2)$$

Under the assumption of no infectious quanta at the beginning of the event, a multiplicative factor, $r_{ss}$, can be applied for events too short to approximately reach steady state (see Section S1 for detail) to correct the deviation of the quanta concentration averaged over the event ($c_{avg}$) from that at steady state:

$$c_{avg} = r_{ss} E_p f_e / (V \lambda) \quad (3)$$

Since the goal is to analyze outbreaks, we assume that only a single infectious person is present in the space, which is thought to be applicable to the outbreaks analyzed below. This allows calculation of the probability of infection, *conditional* to one infectious person being present. The model can also be formulated to calculate the *absolute* probability of infection, if we assume that the probability of an infectious person being present reflects the prevalence of a disease at a given location and time (e.g. refs 30 and 36).

The dose expressed in infectious quanta (n) inhaled by each of the susceptible persons present in the space ($N_{sus}$) is then:

$$n = f_i B c_{avg} D \quad (4)$$

where $f_i$ is the penetration efficiency of virus-carrying particles through masks or face coverings for inhalation (which takes into account the effect of the fraction of occupants wearing face coverings); B is the breathing volumetric flow rate of susceptible persons; D is the duration of exposure, assumed to be the same for all the susceptible persons. Substituting:

$$n = r_{ss} E_p f_e f_i B D / (V \lambda) \quad (5)$$

The number of expected secondary infections increases monotonically with increasing n. For an individual susceptible person, by definition of an infectious quantum, the probability of infection is [28]:

$$P = 1 - e^{-n} \quad (6)$$

For low values of n, the use of the Taylor expansion for an exponential allows approximating P as:

$$P \sim n \quad (7)$$

And the total number of secondary infections expected is then:

$$N_{si} = P\, N_{sus} \sim n\, N_{sus} \quad (8)$$

Thus, the number of secondary infections increases linearly with n at lower values, and non-linearly at higher values. We retain the simplified form to define and calculate the risk parameters, but use equation (6) for fitting the outbreak results in Figure 1b below.

**Risk parameters for airborne infection**

We define the hazard parameter, H, for airborne infection in a shared space. The purpose of H is to capture the dependency of $N_{si}$ on the parameters that define an event in a given space, in particular those parameters that can be controlled to reduce risk. To better capture the controllable actions, $E_p$ and B were split into factors that can and cannot be controlled. $E_p$ can be expressed as the product $E_{p0}$ x $r_E$ where $E_{p0}$ and $r_E$ are, respectively, the quanta shedding rate of an infectious person resting and only orally breathing (no vocalization); and the shedding rate enhancement factor relative to $E_{p0}$ for an activity with a certain degree of vocalization and physical intensity (see Table S2a for detail). B can be expressed as $B_0$ x $r_B$, where $B_0$ and $r_B$ are the volumetric breathing rate of a sedentary susceptible person in the age group of 41-<51

years (numerically also the average for all age groups) and the relative breathing rate enhancement factor (vs. $B_0$) for an activity with a certain physical intensity and for a certain age group (see Table S2b for detail). $E_{p0}$ is uncertain, likely highly variable across the population, and variable over time during the period of infectiousness.[31,35,37] It may also increase due to new virus variants such as the COVID-19 B1.1.7 variant, that are more contagious, assuming that the increased contagiousness is due to increased viral emission or reduced infectious dose (both of which would increase the quanta emission rate).[38,39] We note that some variants could in principle also increase transmissibility by lengthening the period of infectiousness for a given person, which by itself would not increase the quanta emission rate in a given situation. $B_0$ is relatively well known, and varies with a susceptible person's age, sex, and body weight, in addition to physical activity level. $r_E$ and $r_B$ are less uncertain than $E_{p0}$ and are functions of the specific physical and vocalization activities.[31,35,40] Thus, they are useful in capturing the quantitative impact of specific controllable factors. There could be factors beyond those considered here that lead to variation of viral emissions, such as respiratory effort of patients with breathing disorders such as pneumonia or asthma.[41] Such factors can be incorporated into updated Tables in the future.

Then P and $N_{si}$ can be expressed as functions of $E_{p0}$, $B_0$ and the product of the other controllable factors as:

$$N_{si} = E_{p0}\, B_0\, H \qquad (9)$$

Where H is the hazard parameter:

$$H = r_{ss}\, r_E\, r_B\, f_e\, f_i\, D\, N_{sus} / (V\, \lambda) \qquad (10)$$

The four terms that make up λ may vary in relative importance for different diseases and conditions. $\lambda_{dec}$ ~ 1.1 $h^{-1}$ [42] has been reported for COVID-19. $\lambda_{dec}$ depends on temperature and relative humidity.[43,44] $\lambda_{dep}$ depends on particle size and the geometry and airflow in a given space. Respiratory particle sizes in the range from 1-5 μm are thought to play a role in aerosol transmission of COVID-19, due to a combination of high emission rates by activities such as talking[45] and low deposition rates. $\lambda_{dep}$ for a typical furnished indoor space span 0.2-2 $h^{-1}$ over this size range, with faster deposition for larger particles.[46] $\lambda_0$ varies from ~12 $h^{-1}$ for airborne infection isolation rooms,[47] ~6 $h^{-1}$ for laboratories, ~0.5 $h^{-1}$ for residences,[48] and ~1 $h^{-1}$ for offices.[1,49] Very little ventilation data is available for many semi-public spaces such as retail, restaurants and bars or transportation. $\lambda_{cle}$ can vary from 0, if such systems are not in use, to several $h^{-1}$ for adequately sized systems. Ventilation with clean outdoor air will be important in most situations, while virus decay and deposition likely contribute but are more uncertain for COVID-19, based on current information. In particular, the size distribution of aerosols containing infectious viruses is uncertain.

We consider a worst-case scenario where rates of deposition and infectivity decay are small compared with ventilation and air cleaning and can therefore be neglected. This also allows using the same risk parameter to compare different airborne diseases. This yields:

$$H \sim r_{ss}\, r_E\, r_B\, f_e\, f_i\, D\, N_{sus} / (V\, (\lambda_0 + \lambda_{cle})) \qquad (11)$$

H can be recast as:

$$H \sim r_{ss}\, r_E\, r_B\, f_e\, f_i\, D / L \qquad (12)$$

where:

$$L = V (\lambda_0 + \lambda_{cle}) / N_{sus} \quad (13)$$

Assuming that all of the people present in a space are susceptible to infection, L is equivalent to the ventilation plus air cleaning rate per person present in the space, (typically expressed in liters $s^{-1}$ $person^{-1}$ in guidelines such as from refs 50–52. If some fraction of the people present are immune to the disease, then L is larger than the corresponding personal ventilation rate in the guidance. While this recasting will be useful to persons familiar with ventilation guidelines, we keep the form in equation (11) for most further analyses, since the number of people allowed in a space is one of the critical variables that can be examined with this risk parameter.

We define another parameter,

$$H' = r_{ss} D / L \quad (14)$$

which does not depend on activity type or face covering choice and only captures the characteristics of susceptible people's presence in the indoor space, not of their behavior.

For the infection risk of individuals in the presence of one infector, we define the relative risk parameter, a third parameter proportional to the conditional probability of infection, $H_r$, as follows:

$$H_r = r_{ss} r_E r_B f_e f_i D / (V (\lambda_0 + \lambda_{cle})) \quad (15)$$

When it is unknown whether an infector is present, H is an approximate indicator of the absolute probability of infection ($P_a$), since the expected value of number of infectors ($N_i$) is the product of

number of occupants (N) and probability of an occupant being infectious, a measure of prevalence of infectious people in local population ($\eta_I$). Then,

$$P_a = N_i\, r_{ss}\, E_p\, f_e\, f_i\, B\, D / (V\, \lambda) = \eta_I\, N\, r_{ss}\, E_{p0}\, B_0\, r_E\, r_B\, f_e\, f_i\, D / (V\, \lambda)$$
$$\approx \eta_I\, N_{sus}\, H_r\, E_{p0}\, B_0 = \eta_I\, E_{p0}\, B_0\, H \qquad (16)$$

For a situation with multiple potential infectors present (e.g. a COVID ward in a hospital), the risk parameters should be multiplied by the number of infectors.

**Value of the risk parameters for documented outbreaks of COVID-19**

An important advantage of the simplified risk parameters is that their values can be calculated for outbreaks that are documented in the scientific literature. Values for documented COVID-19 outbreaks are shown in Table 1 ($r_E$ and $r_B$ are estimated based on the likely types of activities in each case,[31,35,40] see Table S2 for typical values). Also included are values for outbreaks documented in the literature for tuberculosis and measles, which are widely accepted to transmit through the air, and an influenza outbreak that was clearly due to airborne transmission. A limitation is that many outbreak reports have no information on ventilation or room volume. It is important that future outbreak reports include this information, to allow expanding our knowledge of the circumstances conducive to airborne transmission of different diseases.

| Disease | Outbreak (reference) | $r_E$ Relative shedding rate factor | $r_B$ Relative breathing rate factor | D (h) | $N_{sus}$ | V ($m^3$) | $\lambda_0$ ($h^{-1}$) | L (liter $s^{-1}$ $person^{-1}$) | $r_{ss}$ | H (persons $h^2$ $m^{-3}$) | H' (persons $h^2$ $m^{-3}$) | $H_r$ ($h^2$ $m^{-3}$) | Attack rate (%) | Number of secondary cases |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COVID-19 | Guangzhou restaurant[4] | 9.3[a] | 1 | 1.2 | 20 | 97 | 0.67 | 0.9 | 0.31 | 1.1 | 0.11 | 0.054 | 45 | 9 |
| | Big bus outbreak[19] (ventilation from pers. comm. Y. Li) | 1 | 1 | 3.3 | 46 | 60 | 4.7 | 1.7 | 0.94 | 0.50 | 0.50 | 0.011 | 17 | 8 |
| | Small bus outbreak[19] (ventilation from pers. comm. Y. Li) | 1 | 1 | 1 | 17 | 22 | 8.9 | 3.2 | 0.89 | 0.077 | 0.077 | 0.0045 | 12 | 2 |
| | Skagit Choir[11] | 85[b] | 2.5[c] | 2.5 | 60 | 810 | 0.7 | 2.6 | 0.53 | 30 | 0.14 | 0.5 | 87 | 53 |
| | Call center[53] | 30[d] | 1 | 8 | 216 | 630 | 6 | 4.9 | 0.98 | 13 | 0.45 | 0.062 | 44 | 94 |
| | Aircraft[54] | 50[e] | 1 | 11 | 19[f] | 60 | 21 | 18 | 1 | 8.4 | 0.17 | 0.44 | 63 | 12 |
| | Slaughterhouse[55] | 4.3[g] | 5[h] | 8 | | 3000 | 0.53 | | 0.77 | | | 0.083 | 26 | |
| | Berlin Choir[56] | 85[b] | 2.5[c] | 2.5 | | 1200 | 0.17 | | 0.19 | | | 0.49 | 91 | |
| | Berlin School 1[56] | 1 | 1 | 4.5 | | 180 | 8.3 | | 0.97 | | | 0.0029 | 10 | |
| | Berlin School 2[56] | 1 | 1 | 1.5 | | 150 | 10 | | 0.93 | | | 0.00093 | 6 | |
| | Israel School[57] | 5.7[i] | 1.1[j] | 4.5 | | 150 | 2.7 | | 0.92 | | | 0.1 | 43 | |
| | Germany Meeting[56] | 1.7[k] | 1 | 2 | | 170 | 1.2 | | 0.62 | | | 0.012 | 17 | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tuberculosis | Office[58] | 1.7[k] | 1 | 160 | 67 | | | 7.1 | 1[l] | 11 | 6.3 | 0.16 | 40 | 27 |
| | Hospital[59] | 1.9[m] | 1.7[n] | 1800 | 25 | 200 | 6 | 13 | 1[l] | 120 | 37.5 | 4.8 | 28 | 7 |
| Influenza | Aircraft[e] [60] | 50 | 1 | 4.3 | 29 | 168 | 0.5 | 0.45 | 0.59 | 44 | 0.88 | 1.5 | 86 | 25 |
| Measles | School[28] | 1 | 1 | 10 | 48 | | | 150[o] (7.6) | 1[l] | 0.019 | 0.019 | 0.0004 | 52 | 25 |
| | School[p] [28] | 1 | 1 | 30 | 31 | | | 170[o] (5.5) | 1[l] | 0.05 | 0.05 | 0.0016 | 23 | 7 |

*Footnotes: choice of parameters for specific cases.* [a] *Talking during half of the time and half normal / half loud talking assumed;* [b] *Light exercise - loudly speaking;* [c] *Light intensity for 61-<71 years;* [d] *Resting - loudly speaking;* [e] *Estimate for coughing. The value is the product of* $r_E$ *for resting - speaking and the ratio of the average expired aerosol counts for coughing and talking;*[61] [f] *only the business class cabin is considered;* [g] *Moderate exercise - oral breathing;* [h] *Moderate intensity for all age groups;* [i] *Standing - speaking for the infectious teacher;* [j] *Sedentary/passive for students aged 12-18;* [k] *Resting - speaking during ⅓ of the time assumed;* [l] *Event long enough for the assumption of unity for* $r_{ss}$*;* [m] *Half resting - oral breathing / half light exercise -oral breathing assumed;* [n] *Half sedentary/passive / half light intensity assumed;* [o] *Ventilation rate per susceptible person. The number in parentheses is for the ventilation rate per occupant, estimated based on a teacher-to-student ratio of 11.3% for Monroe County, NY (according to National Center for Education Statistics Common Core of Data (https://nces.ed.gov/ccd/));* [p] *Scaled to the single-infector condition.*

*Table 1: Parameters for outbreaks documented in the literature. Missing parameters could not be calculated from the information given in the literature references.*

We see that the COVID-19 outbreaks that have been documented span ~2.5 orders of magnitude range of the risk parameter H ~ 0.09-30 persons $h^2$ $m^{-3}$. Numbers of secondary

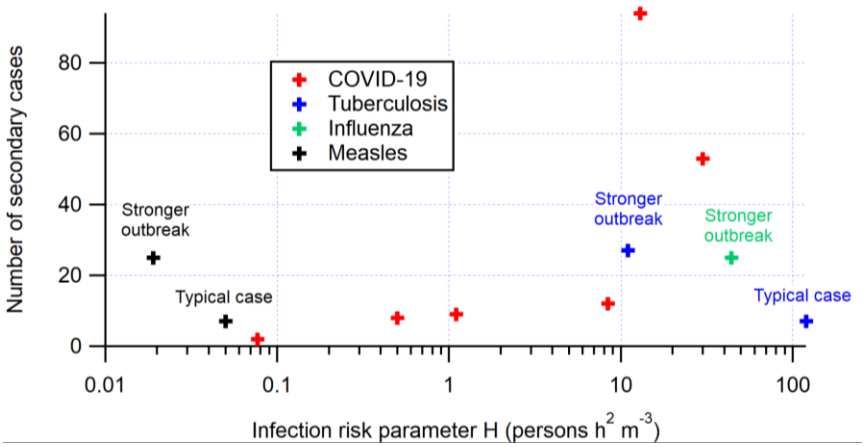
cases of these outbreaks generally increase with H (Figure 1a). Aiming to maintain values far below the threshold of 0.05 persons $h^2$ $m^{-3}$ should help reduce outbreaks.

$H_r$ correlates well with the attack rates for the outbreaks reported in Table 1 (Figure 1b, $H_r$ can be calculated for more literature outbreaks than H). COVID-19 outbreaks are observed for $H_r$ > 0.001 $h^2$ $m^{-3}$, and thus indoor activities should be limited to conditions below this value during the pandemic whenever possible.

A trend line was fitted to the attack rate vs. $H_r$ dataset with the Box/Wells-Riley model, with the fitting parameter being $E_{p0}$, i.e. the basic quanta shedding rate (when breathing only, no vocalization). An $E_{p0}$ of 18.6 quanta $h^{-1}$ was obtained by fitting (with $B_0$ = 0.288 $m^3$ $h^{-1}$ assumed for all occupants for simplicity). This value is higher than that suggested by Buonanno et al. (2 quanta $h^{-1}$),[31,35] but within the uncertainties provided by those authors. The attack rates estimated according to this trend line have a high correlation with the actual attack rates ($r^2$ = 0.90; Figure S1).

The good agreement supports the dominant airborne character of these COVID-19 outbreaks. If the outbreaks had major components of fomite or large droplet transmission, we would expect a dependence on other parameters not considered here and overall much lower correlation with the risk parameters.

*(a)*




*(b)*

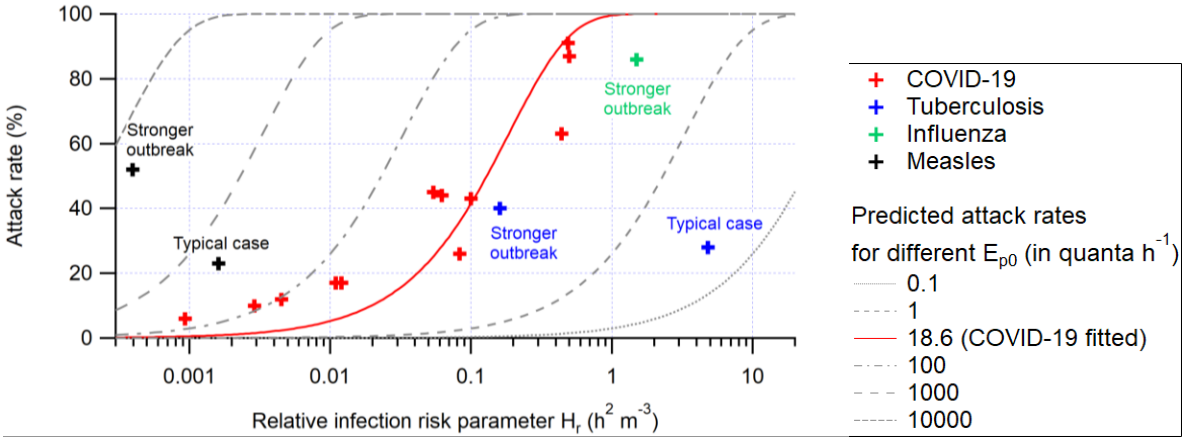



*Figure 1: (a) Number of secondary cases vs. the risk parameter H and (b) attack rate vs. the relative risk parameter $H_r$ for outbreaks of COVID-19, tuberculosis, influenza, and measles reported in the literature.*

**Effect of building parameters vs. human activities**

The type of activity performed in each case (captured by $r_E$ and $r_B$) contributes substantially to the difference in H between these cases. When human activities are not taken into account, the parameter H' only spans a narrow range, 0.09-0.56. This is probably due to similar per-person

ventilation rates in many public indoor spaces (on the order of a few liter $s^{-1}$ $person^{-1}$)[50] and similar lengths of common events (in hours).

Similar to H, the variation in the values of $H_r$ for the outbreaks in Table 1 is also largely due to $r_E$ and $r_B$. If they are not taken into account, $H_r$ for all outbreaks would vary in the narrow range 0.001 to ~0.01 $h^2$ $m^{-3}$, as V and $\lambda_0$ are building characteristics and D, as discussed above, is usually in hours. This implies that, in the presence of a single infector, reducing vocalization and/or physical intensity levels of the indoor activity is a very effective way to lower the infection risk of susceptible individuals. Reducing event length can also help, while reducing occupancy cannot in this case, as shown by equation (15).

It is possible that some of the most visible outbreaks are associated with super-emitter individuals, who shed virus particles at higher rates than others.[41,62–64] If that is the case, the actual $H_r$ values for significant transmission in the presence of individuals that are not super emitters may be higher than those determined here. However, if super-emitters are important, so will be their contribution to total spread, and thus one should try to reduce the risk to reduce the probability of such events occurring.

**Values of the risk parameters for outbreaks of other airborne diseases**

In Table 1 and Figure 1 we also include a few reported indoor outbreaks of three other diseases with significant airborne transmission, i.e., tuberculosis, influenza, and measles. For outbreaks to have a similar number of secondary cases or attack rate, H or $H_r$ needs to be higher for tuberculosis and influenza and lower for measles than that for COVID-19 (Figure 1). Note that many of the children present in the measles outbreak were vaccinated, but the risk parameter framework can still be applied by considering the number of susceptible children present. This

difference is mainly due to differences in $E_{p0}$ (lower for tuberculosis and influenza and higher for measles; Figure 1b). A higher $E_{p0}$ for measles may indicate a larger amount of airborne measles virus in breath or a steeper dose-response curve for the measles virus than SARS-CoV-2, or both. A novel disease as contagious as measles would make almost any indoor situation prone to superspreading. On the other hand, tuberculosis and influenza are less contagious. Tuberculosis transmission is helped because untreated infected people remain contagious for years.[65] The influenza outbreak occurred in an airplane without ventilation with the index case constantly coughing, and represents an extreme for this disease.[60] Most influenza patients emit significantly less virus.[66]

Given that both the measles and tuberculosis pathogens are widely accepted as airborne, the intermediate risk profile for COVID-19 in Figure 1b is not inconsistent with airborne transmission, contrary to frequently made arguments.[67,68] Contagiousness of a disease does not necessarily indicate the transmission route.[69] Airborne diseases can vary in their contagiousness depending on parameters such as the amount of virus shed, the survival of the virus in the air, the dose-response relationship for infection, and other parameters. The only fundamental requirement is that transmission needs to be sufficient for the disease to survive as such, something COVID-19 has had no trouble with so far.

**Graphical representation of relative risks of different situations**

When it is not known whether infectors are present in an indoor event, all occupants need to be considered as possible infectors. We will assume that the probability of an occupant being infectious is the same as the fraction of infectious people in the local population ($\eta_I$). H indicates the risk of an outbreak. Consequently, the risk also depends on occupancy, besides vocalization level, event duration, ventilation, and mask wearing. Jones et al.[25] estimated the dependency of

the infection risk on these factors in a tabulated manner similar as Table 2. However, they only did so qualitatively. Having introduced H as a risk parameter, we can assess the risk more quantitatively based on H values (as well as contact times allowed until outbreak risk is significant (H = 0.05 persons $h^2$ $m^{-3}$) and attack rates) under different conditions (Table 2). Although the actual risk also depends on $\eta_l$ and the choice of the threshold for high risk (red cells in Table 2) is subjective, the risk parameter (H value) in Table 2 seems to vary in a smaller range than the corresponding table in ref 25. We also show that being outdoors (with much better ventilation than indoors) has a greater expected benefit than Jones et al. estimated.

*(a)*

| Type and level of group activity | Low occupancy | | | High occupancy | | |
|---|---|---|---|---|---|---|
| | Outdoor and well ventilated | Indoor and well ventilated | Poorly ventilated | Outdoor and well ventilated | Indoor and well ventilated | Poorly ventilated |
| Wear face coverings, contact for short time | | | | | | |
| Silent | 2.33E-05 | 1.17E-03 | 1.17E-02 | 2.33E-04 | 1.17E-02 | 1.17E-01 |
| Speaking | 1.17E-04 | 5.83E-03 | 5.83E-02 | 1.17E-03 | 5.83E-02 | 5.83E-01 |
| Shouting, singing | 7.00E-04 | 3.50E-02 | 3.50E-01 | 7.00E-03 | 3.50E-01 | 3.50E+00 |
| Heavy exercise | 1.63E-03 | 8.17E-02 | 8.17E-01 | 1.63E-02 | 8.17E-01 | 8.17E+00 |
| Wear face coverings, contact for prolonged time | | | | | | |
| Silent | 2.33E-04 | 1.17E-02 | 1.17E-01 | 2.33E-03 | 1.17E-01 | 1.17E+00 |
| Speaking | 1.17E-03 | 5.83E-02 | 5.83E-01 | 1.17E-02 | 5.83E-01 | 5.83E+00 |
| Shouting, singing | 7.00E-03 | 3.50E-01 | 3.50E+00 | 7.00E-02 | 3.50E+00 | 3.50E+01 |
| Heavy exercise | 1.63E-02 | 8.17E-01 | 8.17E+00 | 1.63E-01 | 8.17E+00 | 8.17E+01 |
| No face coverings, contact for short time | | | | | | |
| Silent | 6.67E-05 | 3.33E-03 | 3.33E-02 | 6.67E-04 | 3.33E-02 | 3.33E-01 |
| Speaking | 3.33E-04 | 1.67E-02 | 1.67E-01 | 3.33E-03 | 1.67E-01 | 1.67E+00 |
| Shouting, singing | 2.00E-03 | 1.00E-01 | 1.00E+00 | 2.00E-02 | 1.00E+00 | 1.00E+01 |
| Heavy exercise | 4.67E-03 | 2.33E-01 | 2.33E+00 | 4.67E-02 | 2.33E+00 | 2.33E+01 |
| No face coverings, contact for prolonged time | | | | | | |
| Silent | 6.67E-04 | 3.33E-02 | 3.33E-01 | 6.67E-03 | 3.33E-01 | 3.33E+00 |
| Speaking | 3.33E-03 | 1.67E-01 | 1.67E+00 | 3.33E-02 | 1.67E+00 | 1.67E+01 |
| Shouting, singing | 2.00E-02 | 1.00E+00 | 1.00E+01 | 2.00E-01 | 1.00E+01 | 1.00E+02 |
| Heavy exercise | 4.67E-02 | 2.33E+00 | 2.33E+01 | 4.67E-01 | 2.33E+01 | 2.33E+02 |

*(b)*

| Type and level of group activity | Low occupancy | | | High occupancy | | |
|---|---|---|---|---|---|---|
| | Outdoor and well ventilated | Indoor and well ventilated | Poorly ventilated | Outdoor and well ventilated | Indoor and well ventilated | Poorly ventilated |
| Wear face coverings | | | | | | |
| Silent | 2142.86 | 42.86 | 4.29 | 214.29 | 4.29 | 0.43 |
| Speaking | 428.57 | 8.57 | 0.86 | 42.86 | 0.86 | 0.09 |
| Shouting, singing | 71.43 | 1.43 | 0.14 | 7.14 | 0.14 | 0.01 |
| Heavy exercise | 30.61 | 0.61 | 0.06 | 3.06 | 0.06 | 0.01 |
| No face coverings | | | | | | |
| Silent | 750.00 | 15.00 | 1.50 | 75.00 | 1.50 | 0.15 |
| Speaking | 150.00 | 3.00 | 0.30 | 15.00 | 0.30 | 0.03 |
| Shouting, singing | 25.00 | 0.50 | 0.05 | 2.50 | 0.05 | 0.01 |
| Heavy exercise | 10.71 | 0.21 | 0.02 | 1.07 | 0.02 | 0.00 |

*(c)*

| Type and level of group activity | Low occupancy | | | High occupancy | | |
|---|---|---|---|---|---|---|
| | Outdoor and well | Indoor and well | Poorly ventilated | Outdoor and well | Indoor and well | Poorly ventilated |
| Wear face coverings, contact for short time | | | | | | |
| Silent | 0.00% | 0.01% | 0.06% | 0.00% | 0.06% | 0.62% |
| Speaking | 0.00% | 0.03% | 0.31% | 0.01% | 0.31% | 3.08% |
| Shouting, singing | 0.00% | 0.19% | 1.86% | 0.04% | 1.86% | 17.10% |
| Heavy exercise | 0.01% | 0.44% | 4.28% | 0.09% | 4.28% | 35.43% |
| Wear face coverings, contact for prolonged time | | | | | | |
| Silent | 0.00% | 0.06% | 0.62% | 0.01% | 0.62% | 6.06% |
| Speaking | 0.01% | 0.31% | 3.08% | 0.06% | 3.08% | 26.84% |
| Shouting, singing | 0.04% | 1.86% | 17.10% | 0.37% | 17.10% | 84.66% |
| Heavy exercise | 0.09% | 4.28% | 35.43% | 0.87% | 35.43% | 98.74% |
| No face coverings, contact for short time | | | | | | |
| Silent | 0.00% | 0.02% | 0.18% | 0.00% | 0.18% | 1.77% |
| Speaking | 0.00% | 0.09% | 0.89% | 0.02% | 0.89% | 8.54% |
| Shouting, singing | 0.01% | 0.53% | 5.22% | 0.11% | 5.22% | 41.47% |
| Heavy exercise | 0.02% | 1.24% | 11.75% | 0.25% | 11.75% | 71.35% |
| No face coverings, contact for prolonged time | | | | | | |
| Silent | 0.00% | 0.18% | 1.77% | 0.04% | 1.77% | 16.35% |
| Speaking | 0.02% | 0.89% | 8.54% | 0.18% | 8.54% | 59.05% |
| Shouting, singing | 0.11% | 5.22% | 41.47% | 1.07% | 41.47% | 99.53% |
| Heavy exercise | 0.25% | 11.75% | 71.35% | 2.47% | 71.35% | 100.00% |

*Table 2: (a) Values of the airborne infection risk parameter (H, in persons $h^2$ $m^{-3}$), (b) contact times corresponding to H = 0.05 persons $h^2$ $m^{-3}$, and (c) predicted attack rates with 0.1% infectious people in local population in shared spaces under different conditions in the similar format of Fig. 3 of ref 25. An additional type of activity ("heavy exercise") is included. Color of a cell varies (a) with H value from green (0 persons $h^2$ $m^{-3}$) via yellow (0.05 persons $h^2$ $m^{-3}$) to red (≥0.5 persons $h^2$ $m^{-3}$), (b) with contact time from red (0.1 h) via yellow (1 h) to green (10 h), and (c) with predicted attack rate from green (0) via yellow (0.01%) to red (0.1%).*

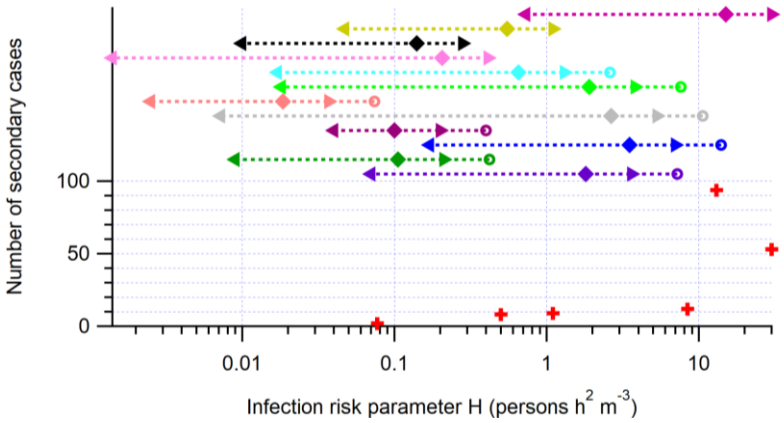
Note that, although occupancy has no impact on attack rate if an infector is present, occupancy affects the risk in two ways when the presence of infector(s) is unknown, i.e., i) the probability of the presence of an infector in a certain locality during a relatively short period (days) and ii) the size (number of secondary cases) of the outbreak if it occurs. Therefore, lowering occupancy has double benefits.

**Risk evaluation for indoor spaces with pre-pandemic and mitigation scenarios**

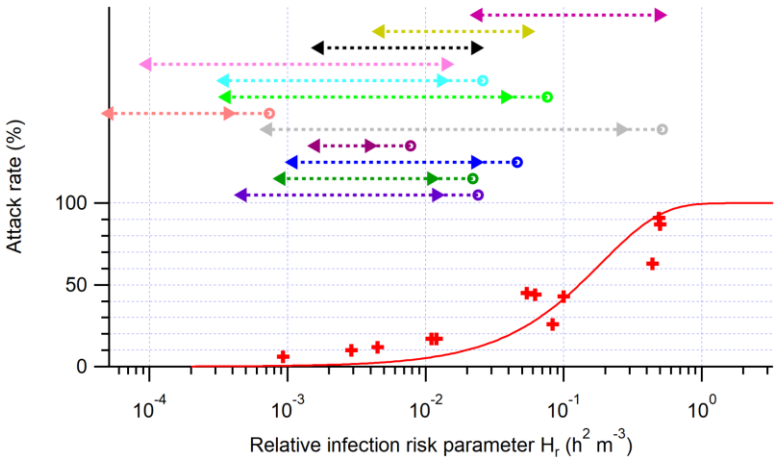
Values of the risk parameter H for some typical public spaces under pre-pandemic conditions are shown in Figure 2 and tabulated in Table S4. H in all pre-pandemic settings is on the order of 0.05 persons $h^2$ $m^{-3}$ or higher, implying significant risk of outbreak during the pandemic. Often, ventilation rates may be lower than official guidance due to e.g. malfunction, lack of maintenance, or attempts to save energy. Substandard ventilation is associated with substantial increases in the risk of outbreak. However, all of the pre-pandemic spaces are in a regime where they are highly sensitive to mitigation efforts. Therefore mitigation measures such as increasing ventilation or air cleaning, reducing voice volume when speaking, reducing occupancy, shortening duration of occupancy and mask wearing are required to reduce the risk

of transmission in similar settings. With mitigation measures implemented, H in these settings can be lowered to the order of 0.01 persons $h^2$ $m^{-3}$, low enough to avoid major outbreaks.

*(a)*




*(b)*



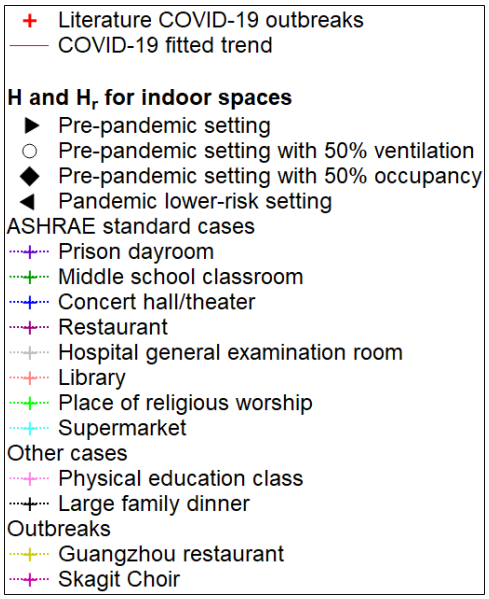




*Figure 2: same format as Figure 1, but for COVID-19 only. Also shown are the H and $H_r$ values for several common indoor situations listed in Table S4. The H values for the cases with pre-pandemic settings except for a lower occupancy and the H and $H_r$ values for the ASHRAE*

*standard cases[50] with pre-pandemic settings except for a lower ventilation rate are shown for comparison.*

### Calculation of risk parameters for specific situations

The calculation of H, H', and $H_r$ for specific situations of interest has been implemented in the COVID-19 aerosol transmission estimator, which is freely available online.[30] The estimator is a series of spreadsheets that implement the same aerosol transmission model described in ref 11 and in this paper. It allows the user to make a copy into an online Google spreadsheet or download it as a Microsoft Excel file for adaptation to the situations of interest to each user. The model can be used to estimate the risk of specific situations, to explore the reduction in transmission due to different control measures (e.g. increased ventilation, masking etc.), and to understand aerosol transmission modeling for incorporation into more complex models. The model also allows the estimation of the average $CO_2$ concentration during an activity, as an additional indicator of indoor risk, and to facilitate the investigation of the relationship between infection risk and $CO_2$ concentrations.[36,70] A screenshot of the estimator is shown in Figure S2.

In addition a sheet allows recalculating Table 2 in this paper for sets of parameters different from those used here (and shown in Table S2).

## Discussion

We have explored the relationship between airborne infection transmission when sharing indoor spaces and the parameters of the space using a box / Wells-Riley model. We have derived an expression for the number of secondary infections, and isolated the controllable terms in this expression in two airborne transmission risk parameters, H and $H_r$.

We find a consistent relationship, with increasing attack rate in the known COVID-19 outbreaks as the value of $H_r$ increases. This provides some confidence that airborne transmission is important in these outbreaks, and that the models used here capture the key processes important for airborne transmission.

When $H_r$ is on order of 0.001 $h^2$ $m^{-3}$ and higher, individual occupants start to have significant COVID-19 infection risk. The lowest H for the major COVID-19 outbreaks in indoor settings reported in the literature is ~0.1 person $h^2$ $m^{-3}$. H can be orders of magnitude higher for the superspreading events where most attendees were infected (e.g. the Skagit Choir0.[11] However, if human activity-dependent factors are not taken into account, H' for all the outbreaks discussed in this paper is ~0.1-0.5 person $h^2$ $m^{-3}$. H' values for public indoor spaces usually fall in or near this range probably due to similar per-person ventilation rates and public event durations. Substandard ventilation is associated with substantial increases in the risk of outbreak. However, all of the pre-pandemic example spaces analyzed are in a regime where they are highly sensitive to mitigation efforts.

The relative risk of COVID-19 infection falls in between two well-known airborne diseases, the more transmissible measles and the less transmissible tuberculosis. This shows that the fact that COVID-19 is less transmissible than measles does not rule out airborne transmission. These risk parameters can be applied for other airborne diseases, once some outbreaks are characterized in this framework. This approach may be useful in the design and renovation of building systems. For a novel disease that was as transmissible as measles, it would be very difficult to make any indoor activities safe.

Our analysis shows that mitigation measures are needed whenever COVID-19 is spreading in a community to limit aerosol transmission risk in most indoor spaces. Among effective measures are reducing vocalization, avoiding intense physical activities, shortening duration, reducing occupancy, wearing high-quality well-fitting masks, increasing ventilation and applying additional virus removal measures (e.g. using HEPA filters). The use of multiple "layers of protection" is needed in many situations, while a single measure (e.g. masking) may not be able to reduce risk to low levels. We have shown that combinations of some or all of these measures are able to lower H close to 0.01 person $h^2$ $m^{-3}$, so that the expected number of secondary cases is substantially lower than 1 even in the presence of an infectious person, hence would be likely to avoid major outbreaks.

**Acknowledgements**

ZP and JLJ were partially supported by NSF AGS-1822664. TG was supported by ESRC ES/V010069/1.

**Competing interests**

The authors declare no competing interests.

**References**

(1) Nazaroff, W. W. Indoor Bioaerosol Dynamics. *Indoor Air* **2016**, *26* (1), 61–78.
(2) Morawska, L.; Cao, J. Airborne Transmission of SARS-CoV-2: The World Should Face the Reality. *Environ. Int.* **2020**, *139*, 105730.
(3) Tellier, R. Review of Aerosol Transmission of Influenza A Virus. *Emerg. Infect. Dis.* **2006**, *12* (11), 1657–1662.
(4) Li, Y.; Qian, H.; Hang, J.; Chen, X.; Cheng, P.; Ling, H.; Wang, S.; Liang, P.; Li, J.; Xiao, S.; Wei, J.; Liu, L.; Cowling, B. J.; Kang, M. Probable Airborne Transmission of SARS-CoV-2 in a Poorly Ventilated Restaurant. *Build. Environ.* **2021**, *196*, 107788.
(5) Public Health England. Varicella: The Green Book, Chapter 34. *Immunisation against infectious disease: London, UK* **2015**.
(6) Tellier, R.; Li, Y.; Cowling, B. J.; Tang, J. W. Recognition of Aerosol Transmission of

Infectious Agents: A Commentary. *BMC Infect. Dis.* **2019**, *19* (1), 101.

(7) Morawska, L.; Milton, D. K. It Is Time to Address Airborne Transmission of Coronavirus Disease 2019 (COVID-19). *Clin. Infect. Dis.* **2020**, *71* (9), 2311–2313.

(8) Lednicky, J. A.; Lauzardo, M.; Fan, Z. H.; Jutla, A.; Tilly, T. B.; Gangwar, M.; Usmani, M.; Shankar, S. N.; Mohamed, K.; Eiguren-Fernandez, A.; Stephenson, C. J.; Alam, M. M.; Elbadry, M. A.; Loeb, J. C.; Subramaniam, K.; Waltzek, T. B.; Cherabuddi, K.; Morris, J. G., Jr; Wu, C.-Y. Viable SARS-CoV-2 in the Air of a Hospital Room with COVID-19 Patients. *Int. J. Infect. Dis.* **2020**, *100*, 476–482.

(9) National Academies of Sciences, Engineering; Medicine; Others. Airborne Transmission of SARS-CoV-2: Proceedings of a Workshop in Brief. The National Academies Press, Washington, DC 2020.

(10) Prather, K. A.; Marr, L. C.; Schooley, R. T.; McDiarmid, M. A.; Wilson, M. E.; Milton, D. K. Airborne Transmission of SARS-CoV-2. *Science* **2020**, *370* (6514), 303–304.

(11) Miller, S. L.; Nazaroff, W. W.; Jimenez, J. L.; Boerstra, A.; Buonanno, G.; Dancer, S. J.; Kurnitski, J.; Marr, L. C.; Morawska, L.; Noakes, C. Transmission of SARS-CoV-2 by Inhalation of Respiratory Aerosol in the Skagit Valley Chorale Superspreading Event. *Indoor Air* **2021**, *31* (2), 314–323.

(12) Greenhalgh, T.; Jimenez, J. L.; Prather, K. A.; Tufekci, Z.; Fisman, D.; Schooley, R. Ten Scientific Reasons in Support of Airborne Transmission of SARS-CoV-2. *Lancet* **2021**. https://doi.org/10.1016/S0140-6736(21)00869-2.

(13) Tang, J. W.; Marr, L. C.; Li, Y.; Dancer, S. J. Covid-19 Has Redefined Airborne Transmission. *BMJ* **2021**, *373*, n913.

(14) Gelfand, H. M.; Posch, J. The Recent Outbreak of Smallpox in Meschede, West Germany. *Am. J. Epidemiol.* **1971**, *93* (4), 234–237.

(15) Yu, I. T. S.; Li, Y.; Wong, T. W.; Tam, W.; Chan, A. T.; Lee, J. H. W.; Leung, D. Y. C.; Ho, T. Evidence of Airborne Transmission of the Severe Acute Respiratory Syndrome Virus. *N. Engl. J. Med.* **2004**, *350* (17), 1731–1739.

(16) Dick, E. C.; Jennings, L. C.; Mink, K. A.; Wartgow, C. D.; Inhorn, S. L. Aerosol Transmission of Rhinovirus Colds. *J. Infect. Dis.* **1987**, *156* (3), 442–448.

(17) Chen, W.; Zhang, N.; Wei, J.; Yen, H.-L.; Li, Y. Short-Range Airborne Route Dominates Exposure of Respiratory Infection during Close Contact. *Build. Environ.* **2020**, *176* (January), 106859.

(18) Katelaris, A. L.; Wells, J.; Clark, P.; Norton, S.; Rockett, R.; Arnott, A.; Sintchenko, V.; Corbett, S.; Bag, S. K. Epidemiologic Evidence for Airborne Transmission of SARS-CoV-2 during Church Singing, Australia, 2020. *Emerg. Infect. Dis.* **2021**, *27* (6). https://doi.org/10.3201/eid2706.210465.

(19) Shen, Y.; Li, C.; Dong, H.; Wang, Z.; Martinez, L.; Sun, Z.; Handel, A.; Chen, Z.; Chen, E.; Ebell, M. H.; Wang, F.; Yi, B.; Wang, H.; Wang, X.; Wang, A.; Chen, B.; Qi, Y.; Liang, L.; Li, Y.; Ling, F.; Chen, J.; Xu, G. Community Outbreak Investigation of SARS-CoV-2 Transmission Among Bus Riders in Eastern China. *JAMA Intern. Med.* **2020**, *180* (12), 1665–1671.

(20) Kwon, K. S.; Park, J. I.; Park, Y. J.; Jung, D. M.; Ryu, K. W.; Lee, J. H. Evidence of Long-Distance Droplet Transmission of SARS-CoV-2 by Direct Air Flow in a Restaurant in Korea. *J. Korean Med. Sci.* **2020**, *35* (46), e415.

(21) Jang, S.; Han, S. H.; Rhee, J. Y. Cluster of Coronavirus Disease Associated with Fitness Dance Classes, South Korea. *Emerg. Infect. Dis.* **2020**, *26* (8), 1917–1920.

(22) Eichler, N.; Thornley, C.; Swadi, T.; Devine, T.; McElnay, C.; Sherwood, J.; Brunton, C.; Williamson, F.; Freeman, J.; Berger, S.; Ren, X.; Storey, M.; de Ligt, J.; Geoghegan, J. L. Transmission of Severe Acute Respiratory Syndrome Coronavirus 2 during Border Quarantine and Air Travel, New Zealand (Aotearoa). *Emerg. Infect. Dis.* **2021**, *27* (5). https://doi.org/10.3201/eid2705.210514.

(23) Nissen, K.; Krambrich, J.; Akaberi, D.; Hoffman, T.; Ling, J.; Lundkvist, Å.; Svensson, L.; Salaneck, E. Long-Distance Airborne Dispersal of SARS-CoV-2 in COVID-19 Wards. *Sci. Rep.* **2020**, *10* (1), 19589.

(24) Hwang, S. E.; Chang, J. H.; Oh, B.; Heo, J. Possible Aerosol Transmission of COVID-19 Associated with an Outbreak in an Apartment in Seoul, South Korea, 2020. *Int. J. Infect. Dis.* **2021**, *104*, 73–76.

(25) Jones, N. R.; Qureshi, Z. U.; Temple, R. J.; Larwood, J. P. J.; Greenhalgh, T.; Bourouiba, L. Two Metres or One: What Is the Evidence for Physical Distancing in Covid-19? *BMJ* **2020**, *370*, m3223.

(26) Morawska, L.; Tang, J. W.; Bahnfleth, W.; Bluyssen, P. M.; Boerstra, A.; Buonanno, G.; Cao, J.; Dancer, S.; Floto, A.; Franchimon, F.; Haworth, C.; Hogeling, J.; Isaxon, C.; Jimenez, J. L.; Kurnitski, J.; Li, Y.; Loomans, M.; Marks, G.; Marr, L. C.; Mazzarella, L.; Melikov, A. K.; Miller, S.; Milton, D. K.; Nazaroff, W.; Nielsen, P. V.; Noakes, C.; Peccia, J.; Querol, X.; Sekhar, C.; Seppänen, O.; Tanabe, S.-I.; Tellier, R.; Tham, K. W.; Wargocki, P.; Wierzbicka, A.; Yao, M. How Can Airborne Transmission of COVID-19 Indoors Be Minimised? *Environ. Int.* **2020**, *142*, 105832.

(27) Bond, T. C.; Bosco-Lauth, A.; Farmer, D. K.; Francisco, P. W.; Pierce, J. R.; Fedak, K. M.; Ham, J. M.; Jathar, S. H.; VandeWoude, S. Quantifying Proximity, Confinement, and Interventions in Disease Outbreaks: A Decision Support Framework for Air-Transported Pathogens. *Environ. Sci. Technol.* **2021**, *55* (5), 2890–2898.

(28) Riley, E. C.; Murphy, G.; Riley, R. L. Airborne Spread of Measles in a Suburban Elementary School. *Am. J. Epidemiol.* **1978**, *107* (5), 421–432.

(29) Noakes, C. J.; Sleigh, P. A. Mathematical Models for Assessing the Role of Airflow on the Risk of Airborne Infection in Hospital Wards. *Journal of The Royal Society Interface*. 2009. https://doi.org/10.1098/rsif.2009.0305.focus.

(30) Jimenez, J. L.; Peng, Z. COVID-19 Aerosol Transmission Estimator https://tinyurl.com/covid-estimator (accessed Mar 26, 2021).

(31) Buonanno, G.; Morawska, L.; Stabile, L. Quantitative Assessment of the Risk of Airborne Transmission of SARS-CoV-2 Infection: Prospective and Retrospective Applications. *Environ. Int.* **2020**, *145*, 106112.

(32) Lelieveld, J.; Helleis, F.; Borrmann, S.; Cheng, Y.; Drewnick, F.; Haug, G.; Klimach, T.; Sciare, J.; Su, H.; Pöschl, U. Model Calculations of Aerosol Transmission and Infection Risk of COVID-19 in Indoor Environments. *Int. J. Environ. Res. Public Health* **2020**, *17* (21), 8114.

(33) Jones, B.; Sharpe, P.; Iddon, C.; Hathway, E. A.; Noakes, C. J.; Fitzgerald, S. Modelling Uncertainty in the Relative Risk of Exposure to the SARS-CoV-2 Virus by Airborne Aerosol Transmission in Well Mixed Indoor Air. *Build. Environ.* **2021**, *191*, 107617.

(34) Han, E.; Tan, M. M. J.; Turk, E.; Sridhar, D.; Leung, G. M.; Shibuya, K.; Asgari, N.; Oh, J.; García-Basteiro, A. L.; Hanefeld, J.; Cook, A. R.; Hsu, L. Y.; Teo, Y. Y.; Heymann, D.; Clark, H.; McKee, M.; Legido-Quigley, H. Lessons Learnt from Easing COVID-19 Restrictions: An Analysis of Countries and Regions in Asia Pacific and Europe. *Lancet* **2020**, *396* (10261), 1525–1534.

(35) Buonanno, G.; Stabile, L.; Morawska, L. Estimation of Airborne Viral Emission: Quanta Emission Rate of SARS-CoV-2 for Infection Risk Assessment. *Environ. Int.* **2020**, *141* (April), 105794.

(36) Peng, Z.; Jimenez, J. L. Exhaled CO2 as a COVID-19 Infection Risk Proxy for Different Indoor Environments and Activities. *Environmental Science & Technology Letters* **2021**. https://doi.org/10.1021/acs.estlett.1c00183.

(37) Ma, J.; Qi, X.; Chen, H.; Li, X.; Zhang, Z.; Wang, H.; Sun, L.; Zhang, L.; Guo, J.; Morawska, L.; Grinshpun, S. A.; Biswas, P.; Flagan, R. C.; Yao, M. COVID-19 Patients in Earlier Stages Exhaled Millions of SARS-CoV-2 per Hour. *Clin. Infect. Dis.* **2020**.

https://doi.org/10.1093/cid/ciaa1283.

(38) Volz, E.; Mishra, S.; Chand, M.; Barrett, J. C.; Johnson, R.; Geidelberg, L.; Hinsley, W. R.; Laydon, D. J.; Dabrera, G.; O'Toole, Á.; Amato, R.; Ragonnet-Cronin, M.; Harrison, I.; Jackson, B.; Ariani, C. V.; Boyd, O.; Loman, N. J.; McCrone, J. T.; Gonçalves, S.; Jorgensen, D.; Myers, R.; Hill, V.; Jackson, D. K.; Gaythorpe, K.; Groves, N.; Sillitoe, J.; Kwiatkowski, D. P.; COVID-19 Genomics UK (COG-UK) consortium; Flaxman, S.; Ratmann, O.; Bhatt, S.; Hopkins, S.; Gandy, A.; Rambaut, A.; Ferguson, N. M. Assessing Transmissibility of SARS-CoV-2 Lineage B.1.1.7 in England. *Nature* **2021**, 1–17.

(39) Kidd, M.; Richter, A.; Best, A.; Cumley, N.; Mirza, J.; Percival, B.; Mayhew, M.; Megram, O.; Ashford, F.; White, T.; Moles-Garcia, E.; Crawford, L.; Bosworth, A.; Atabani, S. F.; Plant, T.; McNally, A. S-Variant SARS-CoV-2 Lineage B1.1.7 Is Associated with Significantly Higher Viral Loads in Samples Tested by ThermoFisher TaqPath RT-qPCR. *J. Infect. Dis.* **2021**. https://doi.org/10.1093/infdis/jiab082.

(40) EPA. Chapter 6—Inhalation Rates. In *Exposure Factors Handbook*; U.S. Environmental Protection Agency, 2011.

(41) Edwards, D. A.; Ausiello, D.; Salzman, J.; Devlin, T.; Langer, R.; Beddingfield, B. J.; Fears, A. C.; Doyle-Meyers, L. A.; Redmann, R. K.; Killeen, S. Z.; Maness, N. J.; Roy, C. J. Exhaled Aerosol Increases with COVID-19 Infection, Age, and Obesity. *Proceedings of the National Academy of Sciences* **2021**, *118* (8), e2021830118.

(42) van Doremalen, N.; Bushmaker, T.; Morris, D. H.; Holbrook, M. G.; Gamble, A.; Williamson, B. N.; Tamin, A.; Harcourt, J. L.; Thornburg, N. J.; Gerber, S. I.; Lloyd-Smith, J. O.; de Wit, E.; Munster, V. J. Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. *N. Engl. J. Med.* **2020**, *382* (16), 1564–1567.

(43) Chan, K. H.; Peiris, J. S. M.; Lam, S. Y.; Poon, L. L. M.; Yuen, K. Y.; Seto, W. H. The Effects of Temperature and Relative Humidity on the Viability of the SARS Coronavirus. *Adv. Virol.* **2011**, *2011*, 734690.

(44) Dabisch, P.; Schuit, M.; Herzog, A.; Beck, K.; Wood, S.; Krause, M.; Miller, D.; Weaver, W.; Freeburger, D.; Hooper, I.; Green, B.; Williams, G.; Holland, B.; Bohannon, J.; Wahl, V.; Yolitz, J.; Hevey, M.; Ratnesar-Shumate, S. The Influence of Temperature, Humidity, and Simulated Sunlight on the Infectivity of SARS-CoV-2 in Aerosols. *Aerosol Sci. Technol.* **2021**, *55* (2), 142–153.

(45) Johnson, G. R.; Morawska, L.; Ristovski, Z. D.; Hargreaves, M.; Mengersen, K.; Chao, C. Y. H.; Wan, M. P.; Li, Y.; Xie, X.; Katoshevski, D.; Corbett, S. Modality of Human Expired Aerosol Size Distributions. *J. Aerosol Sci.* **2011**, *42* (12), 839–851.

(46) Thatcher, T. L.; Lai, A. C. K.; Moreno-Jackson, R.; Sextro, R. G.; Nazaroff, W. W. Effects of Room Furnishings and Air Speed on Particle Deposition Rates Indoors. *Atmos. Environ.* **2002**, *36* (11), 1811–1819.

(47) Ninomura, P.; Bartley, J. New Ventilation Guidelines for Health-Care Facilities. *ASHRAE J.* **2001**, *43* (6), 29–33.

(48) Nazaroff, W. W. Residential Air-Change Rates: A Critical Review. *Indoor Air* **2021**, *31* (2), 282–313.

(49) Persily, A. K.; Gorfain, J.; Brunner, G. Survey of Ventilation Rates in Office Buildings. *Build. Res. Inf.* **2006**, *34* (5), 459–466.

(50) ASHRAE. *Ventilation for Acceptable Indoor Air Quality: ANSI/ASHRAE Standard 62.1-2019*; ANSI/ASHRAE, 2019.

(51) ASHRAE. *ASHRAE Position Document on Infectious Aerosols*; American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2020.

(52) REHVA. *How to Operate HVAC and Other Building Service Systems to Prevent the Spread of the Coronavirus (SARS-CoV-2) Disease (COVID-19) in Workplaces*; Federation of European Heating, Ventilation and Air Conditioning Associations, 2020.

(53) Park, S. Y.; Kim, Y. M.; Yi, S.; Lee, S.; Na, B. J.; Kim, C. B.; Kim, J. I.; Kim, H. S.; Kim,

Y. B.; Park, Y.; Huh, I. S.; Kim, H. K.; Yoon, H. J.; Jang, H.; Kim, K.; Chang, Y.; Kim, I.; Lee, H.; Gwack, J.; Kim, S. S.; Kim, M.; Kweon, S.; Choe, Y. J.; Park, O.; Park, Y. J.; Jeong, E. K. Coronavirus Disease Outbreak in Call Center, South Korea. *Emerg. Infect. Dis.* **2020**, *26* (8), 1666–1670.

(54) Khanh, N. C.; Thai, P. Q.; Quach, H.-L.; Thi, N.-A. H.; Dinh, P. C.; Duong, T. N.; Mai, L. T. Q.; Nghia, N. D.; Tu, T. A.; Quang, L. N.; Quang, T. D.; Nguyen, T.-T.; Vogt, F.; Anh, D. D. Transmission of SARS-CoV 2 During Long-Haul Flight. *Emerg. Infect. Dis.* **2020**, *26* (11), 2617–2624.

(55) Günther, T.; Czech-Sioli, M.; Indenbirken, D.; Robitaille, A.; Tenhaken, P.; Exner, M.; Ottinger, M.; Fischer, N.; Grundhoff, A.; Brinkmann, M. M. SARS-CoV-2 Outbreak Investigation in a German Meat Processing Plant. *EMBO Mol. Med.* **2020**, *12* (12), e13296.

(56) Kriegel, M.; Buchholz, U.; Gastmeier, P.; Bischoff, P.; Abdelgawad, I.; Hartmann, A. Predicted Infection Risk for Aerosol Transmission of SARS-CoV-2. *medRxiv* **2020**, 2020.10.08.20209106.

(57) Stein-Zamir, C.; Abramson, N.; Shoob, H.; Libal, E.; Bitan, M.; Cardash, T.; Cayam, R.; Miskin, I. A Large COVID-19 Outbreak in a High School 10 Days after Schools' Reopening, Israel, May 2020. *Eurosurveillance* **2020**, *25* (29), 1–5.

(58) Nardell, E. A.; Keegan, J.; Cheney, S. A.; Etkind, S. C. Airborne Infection: Theoretical Limits of Protection Achievable by Building Ventilation. *Am. Rev. Respir. Dis.* **1991**, *144* (2), 302–306.

(59) Gammaitoni, L.; Nucci, M. C. Using a Mathematical Model to Evaluate the Efficacy of TB Control Measures. *Emerg. Infect. Dis.* **1997**, *3* (3), 335–342.

(60) Moser, M. R.; Bender, T. R.; Margolis, H. S.; Noble, G. R.; Kendal, A. P.; Ritter, D. G. An Outbreak of Influenza Aboard a Commercial Airliner. *Am. J. Epidemiol.* **1979**, *110* (1), 1–6.

(61) Wilson, N. M.; Marks, G. B.; Eckhardt, A.; Clarke, A. M.; Young, F. P.; Garden, F. L.; Stewart, W.; Cook, T. M.; Tovey, E. R. The Effect of Respiratory Activity, Non-Invasive Respiratory Support and Facemasks on Aerosol Generation and Its Relevance to COVID-19. *Anaesthesia* **2021**. https://doi.org/10.1111/anae.15475.

(62) Milton, D. K.; Fabian, M. P.; Cowling, B. J.; Grantham, M. L.; McDevitt, J. J. Influenza Virus Aerosols in Human Exhaled Breath: Particle Size, Culturability, and Effect of Surgical Masks. *PLoS Pathog.* **2013**, *9* (3), e1003205.

(63) Lindsley, W. G.; Noti, J. D.; Blachere, F. M.; Thewlis, R. E.; Martin, S. B.; Othumpangat, S.; Noorbakhsh, B.; Goldsmith, W. T.; Vishnu, A.; Palmer, J. E.; Clark, K. E.; Beezhold, D. H. Viable Influenza A Virus in Airborne Particles from Human Coughs. *J. Occup. Environ. Hyg.* **2015**, *12* (2), 107–113.

(64) Yan, J.; Grantham, M.; Pantelic, J.; Bueno de Mesquita, P. J.; Albert, B.; Liu, F.; Ehrman, S.; Milton, D. K. Infectious Virus in Exhaled Breath of Symptomatic Seasonal Influenza Cases from a College Community. *Proceedings of the National Academy of Sciences* **2018**, *115* (5), 1081–1086.

(65) Tiemersma, E. W.; van der Werf, M. J.; Borgdorff, M. W.; Williams, B. G.; Nagelkerke, N. J. D. Natural History of Tuberculosis: Duration and Fatality of Untreated Pulmonary Tuberculosis in HIV Negative Patients: A Systematic Review. *PLoS One* **2011**, *6* (4), e17601.

(66) Bueno de Mesquita, P. J.; Noakes, C. J.; Milton, D. K. Quantitative Aerobiologic Analysis of an Influenza Human Challenge-transmission Trial. *Indoor Air* **2020**, *30* (6), 1189–1198.

(67) Conly, J.; on behalf of the WHO Infection Prevention and Control Research and Development Expert Group for COVID-; Seto, W. H.; Pittet, D.; Holmes, A.; Chu, M.; Hunter, P. R. Use of Medical Face Masks versus Particulate Respirators as a Component of Personal Protective Equipment for Health Care Workers in the Context of the COVID-19 Pandemic. *Antimicrob. Resist. Infect. Control* **2020**, *9* (1), 126.

(68) Klompas, M.; Baker, M. A.; Rhee, C. Airborne Transmission of SARS-CoV-2: Theoretical

Considerations and Available Evidence. *JAMA* **2020**, *324* (5), 441–442.

(69) Tang, J. W.; Bahnfleth, W. P.; Bluyssen, P. M.; Buonanno, G.; Jimenez, J. L.; Kurnitski, J.; Li, Y.; Miller, S.; Sekhar, C.; Morawska, L.; Marr, L. C.; Melikov, A. K.; Nazaroff, W. W.; Nielsen, P. V.; Tellier, R.; Wargocki, P.; Dancer, S. J. Dismantling Myths on the Airborne Transmission of Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2). *J. Hosp. Infect.* **2021**, *110*, 89–96.

(70) Rudnick, S. N.; Milton, D. K. Risk of Indoor Airborne Infection Transmission Estimated from Carbon Dioxide Concentration. *Indoor Air* **2003**, *13* (3), 237–245.