Instructions for the Spreadsheet COVID19_Indoor_Safety_Guideline_v5.xslx

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The spreadsheet and the online app [1] enable the calculation of the suggested maximum cumulative exposure times for specific indoor spaces [2]. The input parameters, colored in pink in the spreadsheet and in *italics* below, are divided into the following four categories.

A. Physical Parameters.

The geometry of the indoor space is specified by its *floor area*, A, and *mean ceiling height*, H, from which the volume $V = AH$ is calculated using appropriate unit conversions. The *ventilation outflow rate*, $Q = V\lambda_a$, is calculated from the air exchange rate, λ_a, typically expressed in terms of air changes per hour (ACH). This critical input parameter is governed by national or local standards for different types of indoor spaces, such as the ASHRAE standards (62.1) in the United States [3]. As noted in the main text, natural ventilation may be approximated as $\lambda_a = 0.34$/h, or $1 - 1/e = 62\%$ outdoor air exchange in three hours, which has been measured in bedrooms with closed windows [4] and is considered to be the minimum standard [3], although this value will vary with both location and quality of construction. For residences, classrooms, businesses, and public spaces, λ_a usually falls in the range $4 - 8$/h. Crowded spaces, such as bars, nightclubs and restaurants, typically require more vigorous ventilation, $\lambda_a = 15 - 20$/h. Minimum ventilation standards for American hospitals have increased from 12 to 18 ACH [5]. Most chemical and biological laboratories have λ_a in the range of $6 - 12$/h, but those handling toxic or infectious materials may have λ_a as high as $20 - 30$/h. Revised ASHRAE standards, intended to mitigate the spread of airborne infectious diseases, recommend a minimum of $\lambda_a = 6$/h for all indoor spaces [6].

Forced air filtration and droplet settling in ducts may also be included through the effective air filtration rate, $\lambda_f(r) = p_f(r)\lambda_r$, where $\lambda_r = Q_r/V$ is the *recirculation air exchange rate* passing through the filter and $p_f(r)$ is *droplet filtration probability*, taken to be a constant over the aerosol size range. The United States Environmental Protection Agency defines high-efficiency particulate air (HEPA) filtration [7] as removing $p_f = 99.97\%$ of aerosol particles, while ordinary air filters are assigned Minimum Efficiency Reporting Value (MERV) ratings corresponding to $p_f > 20\%$–90% in specified aerosol size ranges [8]. For ventilation systems with indoor air recirculation, the primary outdoor air fraction, $Z_p = Q/(Q + Q_r)$, is usually specified by indoor air quality (IAQ) standards. For example, $Z_d = 20\%$ for classrooms in the United States [9]), where $Q + Q_r$ is the total flow rate and $v_a = (Q + Q_r)/A$ is the mean air velocity. Alternatively, air filtration may be accomplished by indoor free-standing units with a specified recirculation flow rate of Q_r.

The *relative humidity* RH of the indoor air is another physical input parameter, which affects both respiratory droplet evaporation and viral deactivation [10, 11].

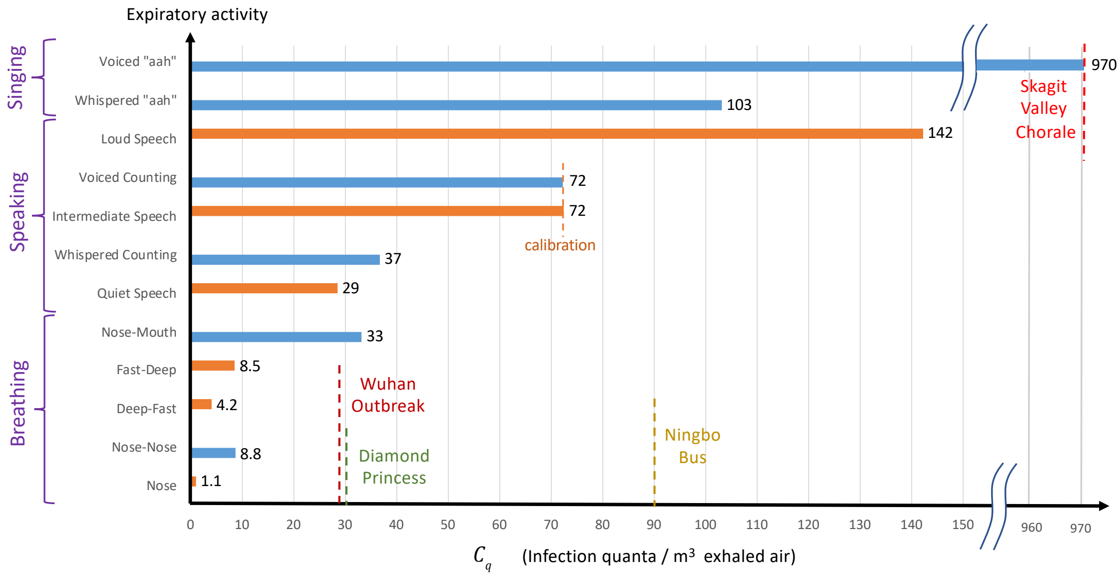

Figure: Estimates of the infectiousness of exhaled air, C_q, the peak concentration of COVID-19 infection quanta in the breath of an infected person, for various respiratory activities. [Reproduced from Fig. 2 of the paper [19].]

B. Physiological Parameters

The first physiological parameter is the *volumetric breathing flow rate*, Q_b, which is approximately 0.5 m^3/h for resting and light activity. Average values for healthy males and females have been reported as 0.49, 0.54, 1.38, 2.35, and 3.30 m^3/h for resting, standing, light exercise, moderate exercise and heavy exercise, respectively [12], and used in simulations of airborne transmission of COVID-19 [13]. The second physiological parameter is the mean respiratory aerosol droplet size $\bar{r}$ for the suspended infectious droplets responsible for airborne disease transmission. The precise definition of $\bar{r}$ is given in Eqs. (4) and (11) of the main text, in terms of the distribution of droplet sizes for different types of respiration [14–16], the size-dependent infectivity of aerosol droplets [17], and the settling and ventilation rates. As illustrated in the main text, a typical value for $\bar{r}$ is 2-3 μm. We note that these values are roughly consistent with the standard definition of aerosol droplets, as those having $r < 5\mu$m [13]. The effect of relative humidity on the size of stable droplets after evaporation [18] can be estimated by rescaling $\bar{r}$ by $\sqrt[3]{0.4/(1-RH)}$, since the droplet distributions used to calibrate the guideline were measured at $RH = 60\%$ [14].

C. Disease Parameters

The most important disease parameter is the *infectiousness of exhaled air*, C_q, the infection quanta per volume. Using all of the limited information currently available, we estimate $C_q = 30$ q/m^3 for normal breathing and light activity and provide our best estimates of C_q for different respiratory activities in the figure. Our analysis indicates that C_q can be an order of magnitude larger for singing or other vigorous respiratory activities, or an order of magnitude smaller for sleeping and light nose breathing.

The second disease parameter is the *viral deactivation rate*, λ_v, at which the aerosol-bound virus loses infectiousness, which for SARS-CoV-2 has been estimated to lie in the range of zero [20] to 0.63/h [21]. Taking into account results for other aerosolized viruses [10, 11, 22], the viral deactivation rate is approximated as linear in relative humidity, $\lambda_v = \lambda_{v,50} RH$, where the value $\lambda_{v,50}$ is specified. The effective viral deactivation rate may also be enhanced by ultraviolet radiation (UV-C) [23] or airborne dispersal of chemical disinfectants (*e.g.* H_2O_2, O_3) [24].

D. Precautionary Parameters

The first precautionary parameter is the *mask filtration factor*, p_m, defined as the fraction of infectious aerosol droplets that pass through the mask during exhalation or inhalation. Many studies are available to help assign this value for different types of face coverings, ranging from cloth coverings to surgical masks [25–28]. Although filtration efficiency depends on drop size, it is typically nearly constant in the aerosol range [25, 26]. Typical values for disposable medical masks are in the range $p_m = 1 - 5\%$ [26, 27], while for simple cloth face masks, $p_m = 10 - 20\%$ [28].

The second precautionary parameter is the *disease transmission tolerance*, ϵ. We note that $\epsilon = 1$ corresponds to the baseline of one expected transmission during the occupancy period. The choice of ϵ should take into account the vulnerability of the population, which for COVID-19 is a strong function of age and pre-existing medical conditions [29–31]. Relative to the median age of 69 in the Skagit Valley Chorale spreading incident used to calibrate our model, the relative rate of hospitalization with COVID-19 [29] can be calculated as 2.5% (ages 0-4), 0.8% (ages 5-17), 20% (ages 18-49), 61% (ages 50-64), 130% (ages 75-84), and 145% (ages > 85). For the elderly, especially those with preexisting conditions or co-morbidity, $\epsilon \ll 1$ should be chosen. For the young and healthy (in regions where hospitals are not overwhelmed and vulnerable groups are protected), larger values of ϵ could be considered [32]. As noted in the main text, choosing a sufficiently small ϵ will also serve to mitigate against prolonged exposure to respiratory jets, whose contribution to pathogen transport may dominate in the absence of face-mask use [33].

E. Results

The spreadsheet first computes properties of the infectious aerosol per infected individual in the room, which are primarily of technical interest: the effective droplet settling speed $v_s(\bar{r})$, the concentration relaxation rate $\lambda_c(\bar{r})$, the dilution factor, f_d, and the infectiousness of the ambient air, $f_d C_q$, in steady state per infected person in the room.

The spreadsheet computes the safety guideline in two ways with the key results highlighted in green. First, the occupancy limit N_{max} can be calculated for a given exposure time τ, as is set by the typical residence time of people in the indoor space. The corresponding minimum outdoor airflow per person, Q/N_{max}, may be compared with local standards, such as 3.8 L/s/person for retail spaces and classrooms and 10 L/s/person for gyms and sports facilities in Europe [34], or the ASHRAE Standards in the United States, typically 5-20 cfm/person depending on the type of space [3]. Second, the time limit τ_{max} is calculated for a given occupancy N. These bounds are plotted and may be compared to the Six-Foot Rule and 15-Minute Rule, both of which invariably violate our guideline. For the bounds on both N_{max} and τ_{max}, two results are reported: the transient bound, which accounts for the buildup of infectious aerosols in the air after the entrance of an infected person, and the more conservative steady-state bound, which is relevant after the relaxation time $\lambda_c \tau \gg 1$.

F. Contact Tracing

The spreadsheet can also be used as a tool for contract tracing. With a conservative tolerance, such as $\epsilon = 0.01$, the guideline defines whether or not the N occupants of a room visited by the index case for a time τ should be considered as contacts for the purpose of tracing the infection network. If the guideline is violated, then *all* occupants of the room must be considered contacts, regardless of their distance from the index case. Compared to the current CDC definition of contact [35] – spending more than 15 minutes less than 6 feet apart from an infected person – this definition, based on our consideration of airborne transmission, may thus identify significantly more contacts to be traced and quarantined.

G. Disclaimer

Our Indoor Safety Guideline calculator is an evolving tool intended to familiarize the interested user with the factors influencing the risk of indoor airborne transmission of COVID-19, and to assist in the quantitative assessment of risk in various settings. We note that uncertainty in and intrinsic variability of model parameters may lead to errors as large as an order of magnitude, which may be compensated for by choosing a sufficiently small risk tolerance. Our guideline does not take into account short-range transmission through respiratory jets, which may substantially elevate risk when face masks are not being worn, in a manner discussed in the main text. Use of the Indoor Safety Guideline is the sole responsibility of the user. It is being made available without guarantee or warranty of any kind. The authors do not accept any liability from its use.

[1] K. Khan, M. Z. Bazant, and J. W. M. Bush, MIT COVID-19 Indoor Safety Guideline, Online app, https://indoor-covid-safety.herokuapp.com (Accessed on November 1, 2020).
[2] Centers for Disease Control and Prevention, www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/social-distancing.html (accessed on July 8, 2020).
[3] *Ventilation and Acceptable Indoor Air Quality in Residential Buildings* (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2016), aSHRAE Standard 62.2.
[4] J. Hou, Y. Sun, Q. Chen, R. Cheng, J. Liu, X. Shen, H. Tan, H. Yin, K. Huang, Y. Gao, et al., Indoor air **29**, 828 (2019).
[5] P. Ninomura and J. Bartley, ASHRAE journal **43**, 29 (2001).
[6] *Ashrae position document on infectious aerosols* (2020).
[7] E. S. Mousavi, K. J. G. Pollitt, J. Sherman, and R. A. Martinello, Building and Environment p. 107186 (2020).
[8] U. S. Environmental Protecion Agency, https://www.epa.gov/indoor-air-quality-iaq/what-hepa-filter-1 (accessed on September 1, 2020).
[9] J. Zhang, Science and Technology for the Built Environment **26**, 1013 (2020).
[10] W. Yang and L. C. Marr, PLOS ONE **6**, 1 (2011).
[11] K. Lin and L. C. Marr, Environmental Science & Technology **54**, 1024 (2019).
[12] W. C. Adams, *Measurement of breathing rate and volume in routinely performed daily activities: Final report, contract no. A033-205* (California Air Resources Board, Sacramento, CA, 1993).
[13] G. Buonanno, L. Stabile, and L. Morawska, Environment International **141**, 105794 (2020).
[14] L. Morawska, G. Johnson, Z. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, C. Chao, Y. Li, and D. Katoshevski, Journal of Aerosol Science **40**, 256 (2009).
[15] S. Asadi, A. S. Wexler, C. D. Cappa, S. Barreda, N. M. Bouvier, and W. D. Ristenpart, Scientific Reports **9**, 1 (2019).
[16] S. Asadi, A. S. Wexler, C. D. Cappa, S. Barreda, N. M. Bouvier, and W. D. Ristenpart, PloS one **15**, e0227699 (2020).
[17] J. L. Santarpia, V. L. Herrera, D. N. Rivera, S. Ratnesar-Shumate, S. Reid, P. W. Denton, J. Martens, Y. Fang, N. Conoan, M. V. Callahan, et al., medRxiv preprint (2020).
[18] R. R. Netz, The Journal of Physical Chemistry B **124**, 7093 (2020).
[19] M. Z. Bazant and J. W. M. Bush, medRxiv preprint (2020).
[20] A. C. Fears, W. B. Klimstra, P. Duprex, A. Hartman, S. C. Weaver, K. Plante, D. Mirchandani, J. Plante, P. V. Aguilar, D. Fernandez, et al., medRxiv preprint (2020).
[21] N. Van Doremalen, T. Bushmaker, D. H. Morris, M. G. Holbrook, A. Gamble, B. N. Williamson, A. Tamin, J. L. Harcourt, N. J. Thornburg, S. I. Gerber, et al., New England Journal of Medicine **382**, 1564 (2020).
[22] L. C. Marr, J. W. Tang, J. Van Mullekom, and S. S. Lakdawala, Journal of the Royal Society Interface **16**, 20180298 (2019).
[23] F. J. García de Abajo, R. J. Hernández, I. Kaminer, A. Meyerhans, J. Rosell-Llompart, and T. Sanchez-Elsner, ACS nano **14**, 7704 (2020).
[24] A. Schwartz, M. Stiegel, N. Greeson, A. Vogel, W. Thomann, M. Brown, G. D. Sempowski, T. S. Alderman, J. P. Condreay, J. Burch, et al., Applied Biosafety **25**, 67 (2020).
[25] C.-C. Chen and K. Willeke, American journal of infection control **20**, 177 (1992).
[26] T. Oberg and L. M. Brosseau, American journal of infection control **36**, 276 (2008).
[27] Y. Li, Y. P. Guo, K. C. T. Wong, W. Y. J. Chung, M. D. I. Gohel, and H. M. P. Leung, Journal of multidisciplinary healthcare **1**, 17 (2008).
[28] A. Konda, A. Prakash, G. A. Moss, M. Schmoldt, G. D. Grant, and S. Guha, ACS Nano **14**, 6339 (2020).
[29] S. Garg, MMWR. Morbidity and Mortality Weekly Report **69** (2020).
[30] J. P. Ioannidis, C. Axfors, and D. G. Contopoulos-Ioannidis, medRxiv preprint (2020).
[31] N. Davies, P. Klepac, Y. Liu, et al., Nature Medicine **898** (2020).
[32] American Academy of Pediatrics, June 25, 2020. https://services.aap.org/en/pages/2019-novel-coronavirus-covid-19-infections/clinical-guidance/covid-19-planning-considerations-return-to-in-person-education-in-schools/.
[33] W. Chen, N. Zhang, J. Wei, H.-L. Yen, and Y. Li, Building and Environment p. 106859 (2020).
[34] B. Blocken, T. van Druenen, T. van Hooff, P. Verstappen, T. Marchal, and L. C. Marr, Building and Environment **180**, 107022 (2020).
[35] Centers for Disease Control and Prevention, www.cdc.gov/coronavirus/2019-ncov/php/contact-tracing/contact-tracing-plan/contact-tracing.html (accessed on August 12, 2020).