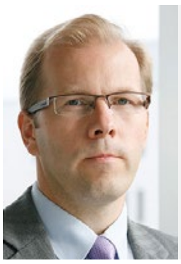
Ventilation rate and room size effects on infection risk of COVID-19



JAREK KURNITSKI
Chair of REHVA Technology and Research Committee
Tallinn University of Technology, Aalto University
jarek.kurnitski@ttu.ee

Available information on COVID-19 shows that transmission of this disease has been associated with close proximity (for which general ventilation isn't the solution) and with spaces that are simply inadequately ventilated. From superspreading events it is known that outdoor air ventilation has been as low as 1–2 L/s per person. In the following it is analysed that is the infection probability in common spaces when ventilation corresponds to about 10 L/s per person recommended in existing standards.

The effect of outdoor air ventilation on virus concentration in the air is illustrated in **Figure 1**. Mixing ventilation reduces very high concentration near the source to a roughly constant level in the room from about 1.5 m distance of the source. Reduction of the virus concentration with effective ventilation allows to control the exposure, i.e. the dose that is closely linked to the infection probability and depends on the breathing rate, concentration and time.

In principle there are two major ways to reduce the dose and infection risk: to increase the ventilation and to reduce the occupancy time. In existing ventilation systems, it is typically not possible to increase the fan speed significantly, so the system can deliver the performance it is sized to do. Sometimes it may be possible to increase total airflow rates by 10–20% overall and by balancing possibly more significantly in specific rooms. In epidemic conditions, obviously demand control has to be overruled and systems should run on nominal or maximum speed. From a legal point of view, the outdoor air ventilation rate must fulfil at least national minimum requirements set in the local building code or other regulatory documents (which may also include specific regulation for COVID-19). If a national ventilation regulation does not exist then typically local building laws will always contain a provision for "good building practice", referring to the use of national, European or international standards and guidelines. Typical sizing according to ISO 17772-1:2017 and EN 16798-1:2019 results in default Indoor Climate Category II to 1.5–2 L/s per floor m² (10–15 L/s per person) outdoor airflow rates in offices and to about 4 L/s per floor m² (8–10 L/s per person) in meeting rooms and classrooms.

Ventilation improvement in existing or new buildings brings a question, are the ventilation rates of Category II enough, or is more outdoor air ventilation needed to reduce the risk of cross-infection? Infection risk is currently not addressed in these standards as design criterion. On the other hand, cross-infection risk is well known and applied in the design of hospital buildings where it leads to ventilation with a 6-12 air change per hour (ACH) rate. Hospital ventilation systems have worked well in COVID-19 conditions as cross-infections have been under control, illustrating that high capacity ventilation is capable to keep aerosol concentration at low level. In non-hospital buildings, there are evidently lower emission rates and smaller numbers of infected persons per floor area. So, a lower ventilation rate than in hospitals, for instance Category I ventilation rate, could be considered as a starting point for the risk reduction. It is also worth noting that 4 L/s per floor m² in meeting rooms and classrooms corresponds to 5 ACH and is not much below the air change rate of patient rooms with precautions against airborne risks.

Probability of infection

Infection risk can be calculated for different activities and rooms using a standard airborne disease transmission Wells-Riley model, calibrated to COVID-19 with correct source strength, i.e., quanta emission rates. In this model, the viral load emitted is expressed in terms of quanta emission rate (E, quanta/h). A quantum is defined as the dose of airborne droplet nuclei required to cause infection in 63% of susceptible persons. With the Wells-Riley model [1], the probability of infection (p) is related to the number of quanta inhaled (n) according to Equation (1):

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

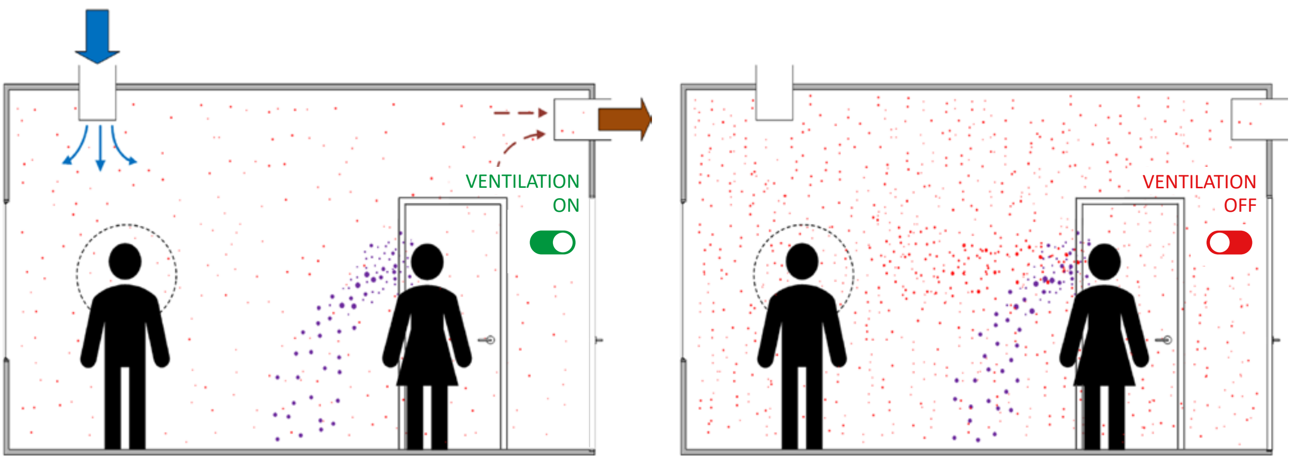


Figure 1. Illustration of how an infected person (speaking woman on the right) leads to aerosol exposure (red spikes) in the breathing zone of another person (man on the left in this case). Large droplet exhalation is marked with purple spikes. When the room is ventilated, the amount of virus-laden particles in the breathing zone is much lower than when the ventilation system is off. Left figure: ventilation system on, right figure: ventilation system off. [Figure courtesy of REHVA]

The quanta inhaled (n, quanta) depends on the time-average quanta concentration (C_{avg}, quanta/m^3), the volumetric breathing rate of an occupant (Q_b, m^3/h) and the duration of the occupancy (D, h):

$$n = C_{avg} Q_b D \tag{2}$$

The airborne quanta concentration increases with time from an initial value of zero following a "one minus exponential" form, which is the standard dynamic response of a fully mixed indoor volume to a constant input source. A fully mixed material balance model for the room can be applied to calculate the concentration:

$$\frac{dC}{dt} = \frac{E}{V} - \lambda C \tag{3}$$

where

- E quanta emission rate (quanta/h);
- V volume of the room (m^3);
- λ first-order loss rate coefficient [2] for quanta/h due to the summed effects of ventilation (λ_v, 1/h), deposition onto surfaces (λ_{dep}, 1/h) and virus decay (k, 1/h);
- C time-dependent airborne concentration of infectious quanta (quanta/m^3).

The surface deposition loss rate of 0.3 1/h may be estimated based on data from [3, 4]. For virus decay Fears [5] shows no decay in virus-containing aerosol for 16 hours at 53% RH, whereas van Doremalen [6] estimated the half-life of airborne SARS-CoV-2 as 1.1 h, which equates to a decay rate of 0.63 1/h. An average value of these two studies is 0.32 1/h.

Assuming the quanta concentration is 0 at the beginning of the occupancy, equation (3) is solved and the average concentration determined as follows:

$$C(t) = \frac{E}{\lambda V}\left(1 - e^{-\lambda t}\right) \tag{4}$$

$$C_{avg} = \frac{1}{D}\int_0^D C(t)\,dt = \frac{E}{\lambda V}\left[1 - \frac{1}{\lambda D}\left(1 - e^{-\lambda D}\right)\right] \tag{5}$$

where

- t time (h)

Calculation examples can be found from papers analysing the Skagit Valley Chorale event [7] and quanta generation rates for SARS-CoV-2 [8]. Quanta emission rates vary over a large range of 3–300 quanta/h depending strongly on activities so that higher values apply for loud speaking, shouting and singing and also for higher metabolism rates, as shown in **Table 1**. Volumetric breathing rates depend on the activity being undertaken as shown in **Table 2**.

Although SARS-CoV-2 quanta/h emission values include some uncertainties, it is already possible to calculate infection risk estimates and conduct comparisons on the effect of ventilation and room parameters. Results from such calculations are shown in **Figure 2** for commonly used ventilation rates and rooms. It is assumed that in all calculated rooms, there is one infected person. The following time-averaged quanta emission rates calculated from activities shown in **Table 1** were used: 5 quanta/h for office work and classroom occupancy, 15 quanta/h for a restaurant, 10 quanta/h for shopping, 21 quanta/h for sports and 19 quanta/h for meeting rooms. While typical COVID-19 infection rates in the general population have been in the magnitude of 1:1000 or 1:10 000, the assumption that only one infected person is in a room that is used by, e.g., 10 (office), 25 (school) or 100 persons (restaurant) is highly valid.

A risk assessment as shown in **Figure 2** helps to build a more comprehensive understanding of how virus laden aerosols may be removed by ventilation. The results show that with Category II ventilation rates according to existing standards, the probability of infection is reasonably low (below 5%) for open-plan offices, classrooms, well-ventilated restaurants, and for short, no more than 1.5-hour shopping trips or meetings in a large meeting room. Small office rooms occupied by 2-3 persons and small meeting rooms show a greater probability of infection, because even in well ventilated small rooms the airflow per infected person is much smaller than that in

Table 1. *90th percentile SARS-CoV-2 quanta emission rates for different activities [9].*

Activity	Quanta emission rate, quanta/h
Resting, oral breathing	3.1
Heavy activity, oral breathing	21
Light activity, speaking	42
Light activity, singing (or loud speaking)	270

Table 2. *Volumetric breathing rates [10, 11].*

Activity	Breathing rate, m^3/h
Standing (office, classroom)	0.54
Talking (meeting room, restaurant)	1.1
Light exercise (shopping)	1.38
Heavy exercise (sports)	3.3

large rooms. Therefore, in an epidemic situation small rooms could be safely occupied by one person only. In normally ventilated rooms occupied by one person there is no infection risk at all because of no emission source. There is also a very visible difference between 1 L/s m² and 2 L/s m² ventilation rate in an open plan office (note that 1 L/s m² is below the standard). Speaking and singing activities are associated with high quanta generation, but also physical exercises increase quanta generation and breathing rate that directly affects the dose. Thus, many of indoor sports facilities (excluding swimming pools and large halls) are spaces with higher probability of infection if not specially designed for high outdoor ventilation rates.

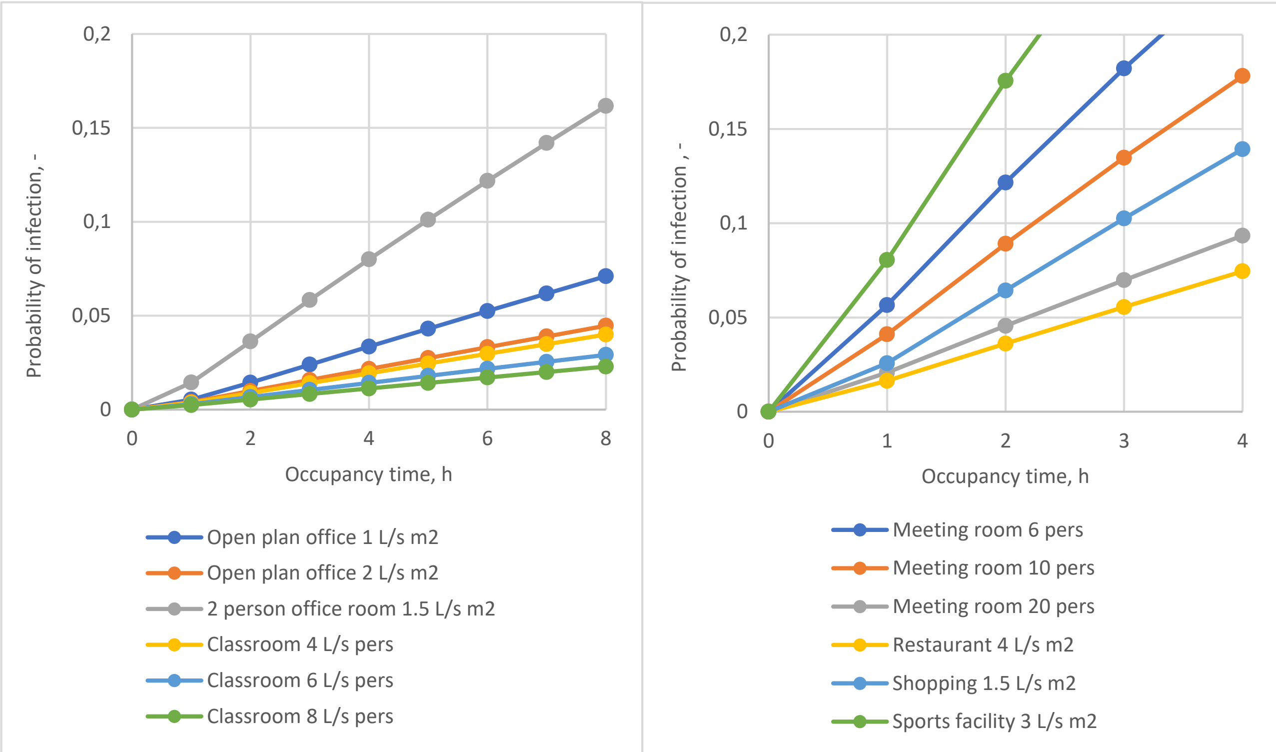


Figure 2. Infection risk assessment for some common non-residential rooms and ventilation rates. 1.5 L/s per m² ventilation rate is used in 2-person office room of 16 m², and 4 L/s per m² in meeting rooms. Detailed input data is reported in Table 3.

Table 3. *Infection risk probability calculation workflow for the cases reported in Figure 2.*

Case Specific Input Parameters													
	Floor area	Height	Ventilation rate per floor area	Quanta emission rate	Breathing rate	Occupancy time	Air change rate	Total first order loss rate	Room volume	x steady state concen-tration	Average concen-tration	Quanta inhaled (dose)	Probability of infection
	A (m²)	h (m)	L/(s m²)	quanta/h	m³/h	Δt (h)	k_{ven} (h^{-1})	k_{tot} (h^{-1})	V (m³)	[ ]	quanta/m³	quanta	–
Open plan office 1 L/s m²	50	3	1	5	0,54	8	1,2	1,82	150	0,93	0,02	0,07	0,071
Open plan office 2 L/s m²	50	3	2	5	0,54	8	2,4	3,02	150	0,96	0,01	0,05	0,045
2 person office room 1.5 L/s m²	16	3	1,5	5	0,54	8	1,8	2,42	48	0,95	0,04	0,18	0,162
Meeting room 6 pers	18	3	4	19	1,1	8	4,8	5,42	54	0,98	0,06	0,56	0,428
Meeting room 10 pers	25	3	4	19	1,1	8	4,8	5,42	75	0,98	0,05	0,40	0,331
Meeting room 20 pers	50	3	4	19	1,1	8	4,8	5,42	150	0,98	0,02	0,20	0,182
Classroom 4 L/s pers	56	3	2	5	0,54	8	2,4	3,02	168	0,96	0,01	0,04	0,040
Classroom 6 L/s pers	56	3	3	5	0,54	8	3,6	4,22	168	0,97	0,01	0,03	0,029
Classroom 8 L/s pers	56	3	4	5	0,54	8	4,8	5,42	168	0,98	0,01	0,02	0,023
Restaurant 4 L/s m²	50	3	4	15	1,1	8	4,8	5,42	150	0,98	0,02	0,16	0,147
Shopping 1.5 L/s m²	50	3	1,5	11	1,38	8	1,8	2,42	150	0,95	0,03	0,32	0,272
Sports facility 3 L/s m²	50	3	3	21	3,3	8	3,6	4,22	150	0,97	0,03	0,85	0,573

Infection risk probability calculation workflow is illustrated in **Table 3**. The total airflow rate is calculated as a product of L/s per floor area ventilation rate value and the floor area, therefore the larger the room the larger the total airflow rate per infected person (1 infected person is assumed in all rooms). It should be noted that the number of occupants has no effect because the calculation is per infected person. The room height (volume) matters on the concentration development so that the source E is switched on at time $t = 0$ and the concentration starts to build up. In the calculation, 8-hour occupancy was considered and the average concentration is quite close to the steady state as the value in the parentheses is higher than 0.9 in all cases (1.0 will correspond to the steady state).

It is important to understand the limitations of the probability calculation:

- Results are sensitive to quanta emission rates which can vary over a large range, as shown in **Table 1**. The uncertainty of these values is high. Also, there are likely to be superspreaders that are less frequent but may have higher emission rates (as in the choir case [7]). This makes absolute probabilities of infection uncertain, and it is better to look at the order-of-magnitude (i.e. is the risk of the order of 0.1% or 1% or 10% or approaching 100%). The relative effect of control measures may be better understood from this calculation, given the current state of knowledge;
- Calculated probability of infection is a statistical value that applies for a large group of persons, but differences in individual risk may be significant depending upon the individual's personal health situation and susceptibility;
- Assuming full mixing creates another uncertainty because, in large and high rooms, the virus concentration is not necessarily equal all over the room volume. In the calculation, a 50 m² floor area is used for an open-plan office. Generally, up to 4 m high rooms with a maximum volume of 300 m³ could be reasonably well mixed; however, it is more accurate to simulate concentrations with CFD analyses. Sometimes thermal plume effects from occupants may provide some additional mixing in high spaces such as theatres or churches.

These limitations and uncertainties mean that rather than predicting an absolute infection risk, the calculation is capable of comparing the relative effectiveness of solutions and ventilation strategies to support the most appropriate choice. Calculation results are easy to convert to the form of relative risk. In **Figure 3**, this is done for an open plan office where 2 L/s per person ventilation rate (0.2 L/s per m²) with occupant density of 10 m² per person is considered as 100% relative risk level. This ventilation rate that is a half of an absolute minimum of 4 L/s per person can be used to describe superspreading events. Results in **Figure 3** show that a common ventilation rate of 2 L/s per m² will reduce the relative risk to 34% and doubling that value to 4 L/s per m² will provide relatively smaller further reduction to 19%.

Finally, **Figure 3** allows to estimate what is the difference between Category II and I ventilation rates. With 10 m² per person occupant density, the airflow rates become 1.4 and 2.0 L/s per m² in Category II and I respectively when low polluting materials are considered. Thus, Category II ventilation results in 43% relative risk and Category I in 34% that shows significant improvement as the curve has quite deep slope at that range.

Conclusions

While there are many possibilities to improve ventilation solutions in future, it is important to recognise that current good practice and knowledge allows the use of many rooms in buildings during a COVID-19 type of outbreak as long as ventilation rates correspond to or ideally exceed existing standards and a cross-infection risk assessment is conducted. Regarding the airflow rates, more ventilation is always better, but to dilute the aerosol concentration the total outdoor airflow rate in L/s per infected person matters. This makes large spaces ventilated according to current standards reasonably safe, but smaller rooms occupied by fewer people and with relatively low airflow rates pose a higher risk even if well ventilated. Limiting the number of occupants in small rooms to one person, reducing occupancy time and applying physical distancing will in most cases keep the probability of cross-infection to a reasonable level. For future buildings and ventilation improvement, Category I ventilation rates can be recommended as these provide significant risk reduction compared to common Category II airflow rates. ■

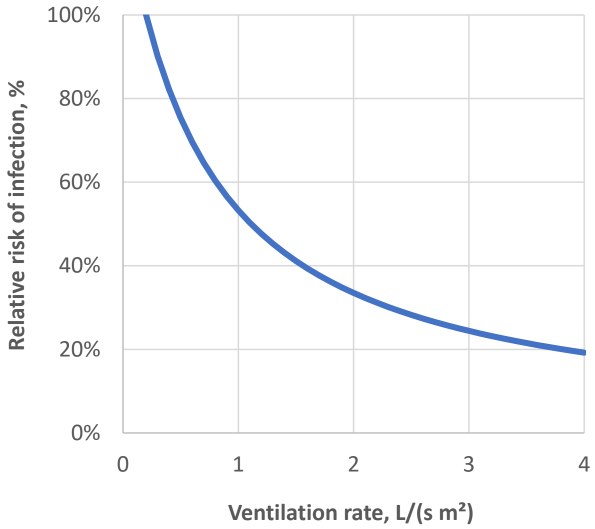


Figure 3. Relative risk in open plan office of 50 m^2 where 2 L/s per person (0.2 L/s per m^2) ventilation rate is considered as a reference level for a superspreading event with 100% relative risk.

References

[1] Nicas M, Nazaroff W, Hubbard A, 2005. Toward Understanding the Risk of Secondary Airborne Infection: Emission of Respirable Pathogens. Journal of Occupational and Environmental Hygiene, 2: 143–154. https://doi.org/10.1080/15459620590918466

[2] Yang W, Marr LC. Dynamics of airborne influenza A viruses indoors and dependence on humidity. *PLoS ONE*. 2011;6:e21481 https://doi.org/10.1371/journal.pone.0021481

[3] Thatcher TL, Lai ACK, Moreno-Jackson R, Sextro RG, Nazaroff WW. Effects of room furnishings and air speed on particle deposition rates indoors. *Atmospheric Environment*. 2002;36:1811–1819.

[4] Diapouli E, Chaloulakou A, Koutrakis P. Estimating the concentration of indoor particles of outdoor origin: A review. *Journal of the Air & Waste Management Association*. 2013;63:1113–1129. https://doi.org/10.1080/10962247.2013.791649

[5] Fears AC, Klimstra WB, Duprex P, et al. Comparative dynamic aerosol efficiencies of three emergent coronaviruses and the unusual persistence of SARS-CoV-2 in aerosol suspensions. *medRxiv* 2020 preprint doi: https://doi.org/10.1101/2020.04.13.20063784.

[6] Doremalen N, Bushmaker T, Morris D, Holbrook M, Gamble A, Williamson B, Tamin A, Harcourt J, Thornburg N, Gerber S, Lloyd-Smith J, de Wit E, Munster V, 2020. Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. N Engl J Med 2020; 382:1564-1567. DOI: 10.1056/NEJMc2004973

[7] 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. (2020). Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event. Indoor Air, 2020, https://doi.org/10.1111/ina.12751 https://doi.org/10.1101/2020.06.15.20132027

[8] Buonannoa G, Stabilea L, Morawska L, 2020 Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment. Environment International 141 (2020) 105794. https://doi.org/10.1016/j.envint.2020.105794

[9] Buonanno G, Morawska L, Stabile L. Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: Prospective and retrospective applications. Environment International 145 (2020) 106112 https://doi.org/10.1016/j.envint.2020.106112

[10] Adams, W.C., 1993. Measurement of Breathing Rate and Volume in Routinely Performed Daily Activities. Final Report. Human Performance Laboratory, Physical Education Department, University of California, Davis. Prepared for the California Air Resources Board, Contract No. A033-205.

[11] Binazzi B, Lanini B, Bianchi R, et al. 2006. Breathing pattern and kinematics in normal subjects during speech, singing and loud whispering. *Acta Physiologica*. 2006; 186: 233–246. https://doi.org/10.1111/j.1748-1716.2006.01529.x