REHVA
Federation of European Heating, Ventilation and Air Conditioning Associations

REHVA COVID-19 Ventilation Calculator documentation (version 2.0, August 1, 2021)

September 2021

Version 2.0 updates

- Quanta emission rate representative values from [13] are changed from 85th percentile of preprint to 66th percentile as reported in the final published paper;
- Virus variant multipliers to deal with British and Delta variant are introduced;
- Complementary measures such as portable air cleaner and facial masks are implemented;
- Probability of infection calculation is extended to the event reproduction number with new curves for model rooms.

Nomenclature

p	probability of infection for susceptibles (-)
N_c	number of disease cases
N_s	the number of susceptible persons in the room
N	total number of persons in the room
I	number of infectious persons
n	quanta inhaled (quanta)
C	time-dependent airborne concentration of infectious quanta (quanta/m^3)
C_{avg}	time-average concentration of infectious quanta (quanta/m^3)
Q_b	volumetric breathing rate of an occupant (m^3/h)
D	duration of the occupancy (h)
η_s	facial mask efficiency for susceptible person (-)
η_i	facial mask efficiency for infected person (-)
η_f	removal efficiency of the room air filter (-)
E	quanta emission rate (quanta/h)
q	quanta emission rate per infected person (quanta/(h pers))
V	volume of the room (m^3)
A	floor area of the room (m^2)
h	room height (m)
λ	first-order loss rate coefficient for quanta/h due to the summed effects of ventilation, deposition onto surfaces, virus decay and possible filtration by portable air cleaner (1/h)
λ_v	outdoor air change rate (1/h)
λ_{dep}	deposition onto surfaces (1/h)
k	virus decay (1/h)
k_f	filtration by portable air cleaner (1/h)
t	time (h)
$t_{1/2}$	half-life of the virus (h)
Q	outdoor air ventilation rate (m^3/h)
Q_f	airflow rate through the filter (m^3/h)
R	event reproduction number (-)
R_0	basic reproduction number (-)

Modelling airborne infection risk

Infection risk can be calculated for different activities and rooms using a standard airborne disease transmission Wells-Riley model calibrated to COVID-19 with the correct source strength (quanta emission rates). In this model, the viral load emitted is expressed in terms of the quantum 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. The model of infection risk due to aerosol transmission is based on the Wells-Riley formulation [1], [2] as amended by Gammaitoni and Nucci [3].

With this modeling approach we introduce the following assumptions and limitations:

- The model assumes that quanta are emitted at a constant rate throughout the event – for ventilation (capacity) sizing purposes we assume that infectious persons (typically one) are present and stay in the room throughout the event;
- In case of full mixing, the infectious respiratory aerosol quickly becomes evenly distributed throughout the well-mixed room air;
- Infectious quanta are removed by ventilation, filtration, deposition, and airborne virus decay;
- The model operates with individual probability of infection of susceptible persons for which acceptable values can be calculated from event reproduction number, however, defining acceptable risk levels for public indoor spaces and community risk assessment are out of the scope of the present work;

With the Wells-Riley model [4], the probability of infection (p) is related to the number of quanta inhaled (n) according to equation (1):

$$p = \frac{N_c}{N_s} = 1 - e^{-n} \tag{1}$$

where

p	the probability of infection for susceptible persons (-)
N_c	the number of disease cases
N_s	the number of susceptible persons in the room
n	quanta inhaled (quanta).

Number of susceptible persons makes no differentiation of high-risk vs. low-risk populations but it is possible to apply stringent probability levels for high-risk groups. To include vaccinated persons, the number of susceptible persons can be reduced assuming 100% efficiency of vaccination. If it is assumed that there are no vaccinated persons in the room the number of susceptible persons becomes $N_s = N - I$ where N is the total number of persons in the room and I is the number of infectious persons.

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):

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

In Equation 2 it is assumed that the breathing rate is a fixed value and in the calculation of the time-average quanta concentration also a fixed quanta emission rate is used. These fixed values describe average values of the event, however in reality somebody can cough or not cough with the same breathing rate and create variation in the emissions. It is hence assumed that the emission rate comes only from breathing or speaking and the concentration in exhaled air is independent of breathing rate and other respiratory activities. If a person is wearing a mask, the facial mask efficiency η_s for a susceptible person reduces the quanta inhaled:

$$n = C_{avg} Q_b (1 - \eta_s) \mathrm{D} \tag{3}$$

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 source. A single zone fully mixed material balance model for the room is applied to calculate the concentration:

$$\frac{dC}{dt} = \frac{E}{V} - \lambda C \quad (4)$$

where

E quanta emission rate (quanta/h)

V volume of the room (m^3)

λ first-order loss rate coefficient [5] for quanta/h due to the summed effects of ventilation (λ_v, 1/h), deposition onto surfaces (λ_{dep}, 1/h), virus decay (k, 1/h) and filtration by a portable air cleaner if applied (k_f, 1/h), $\lambda = \lambda_v + \lambda_{dep} + k + k_f$

C time-dependent airborne concentration of infectious quanta (quanta/m^3).

A fully mixed material balance model is not capable to account spatial concentration variances in the room and may lead to some uncertainties as discussed in Section 5. Ventilation in the loss rate coefficient means all virus free air supplied to the room including outdoor air ventilation, infiltration, virus free air from recirculation and transfer air from other rooms. In the single zone model it is not possible to take into account recirculation for which multi-zone modeling would be needed. In the public indoor spaces with human occupancy under interest, ventilation is typically in balance or supply airflow rate is larger than extract airflow rate, i.e. there is no transfer air to the room. Therefore, in the following, ventilation is treated as an outdoor air ventilation. The quantum emission rate is generated by I infected persons and while accounting for facial mask efficiency, the emission rate can be described as:

$$E = (1 - \eta_i) I q \quad (5)$$

where

I the number of infectious persons

q quanta emission rate per infected person (quanta/(h pers))

η_i facial mask efficiency for infected person, 0 for no mask (-).

The efficiency of a facial mask worn by an infectious person might differ from the efficiency of a mask worn by a susceptible occupant even if they wear nominally identical masks, because the emitted droplets are larger and contain more water than inhaled droplets. For instance, a worst-case mask efficiency values of 0.5 for an infected person and 0.3 for a susceptible person have been measured by Ueki et al. [6].

A surface deposition loss rate of 0.3 1/h may be estimated based on data from Thatcher et al. and Diapouli et al. [7], [8]. For virus decay in the case of no sunlight, Fears et al. [9] reported no decay in virus-containing aerosol for 16 hours at 53% relative humidity, whereas van Doremalen et al. [10] estimated the half-life of airborne SARS-CoV-2 as 1.1 h, which equates to a decay rate $k = \ln(2)/t_{1/2}$ of 0.63 1/h.

For a portable air cleaner, the filtration removal rate (k_f) depends on the rate of airflow through the filter (Q_f), and the removal efficiency of the filter (η_f), V being a room volume:

$$k_f = \frac{Q_f \eta_f}{V} \quad (6)$$

For portable cleaners with a high-efficiency particle air (HEPA) filter, the clean air delivery rate (CADR, m^3/h) is provided and the filtration removal rate can be calculated as $k_f = CADR/V$. It should

be noted that the removal efficiency of filters and the CADR are particle-size dependent. These parameters are to be estimated based on the size distribution of virus-containing particles.

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

$$C(t) = \frac{E}{\lambda V}\left(1 - e^{-\lambda t}\right) \quad (7)$$

$$C_{avg} = \frac{1}{D}\int_0^D C(t)\,dt = \frac{E}{\lambda V}\left[1 - \frac{1}{\lambda D}\left(1 - e^{-\lambda D}\right)\right] \quad (8)$$

where

t time (h).

If steady state is assumed, equations (7) and (8) will simplify so that terms in round and square brackets are equal to one. Calculation examples with these equations can be found in studies analysing the Skagit Valley Chorale event [11] and quanta emission rates for SARS-CoV-2 [12]. It is reported in Buonanno et al. [13] that quanta emission rates vary over a large range depending strongly on the activity; higher values apply for loud speaking, shouting and singing and also for higher metabolism rates. At specific activity, quanta emission from infectious person has a probability distribution, from which not median but 66th percentile values (Table 1) are to be used to calculate the resulting effect for exposure scenarios with constant ventilation and occupancy [13]. Values in Table 1 can be compared with quanta emission rates of 1–10 quanta/h for the common cold/rhinovirus [14], and 0.1-0.2 quanta/h on average, but 630 quanta/h max daily rate for Influenza [15]. Hence they show that SARS-CoV-2 quanta values for resting and not speaking are of the same order of magnitude. Volumetric breathing rates depend on the activity being undertaken as shown in **Error! Reference source not found.**.

Activity	Quanta emission rate q, quanta/(h pers)
Resting, oral breathing	0.72
Heavy activity, oral breathing	4.9
Light activity, speaking	9.7
Light activity, singing (or loudly speaking)	62

Table 1 1. 66th percentile SARS-CoV-2 quanta emission rates for different activities [13]

Activity	Breathing rate Q_b, m^3/h
Standing (office, classroom)	0.54
Talking (meeting room, restaurant)	1.10
Light exercise (shopping)	1.38
Heavy exercise (sports)	3.30

Table 2. Volumetric breathing rates [16], [17].

There are many possible considerations as to how the target acceptable probability of infection level can be selected. As recommended in [18] and [19], an acceptable probability level for a specific room can be defined based on the event reproduction number R. R is defined as number of new disease cases divided by number of infectors. Considering that the number of new cases $N_c = p\,N_s$ an acceptable individual probability for a specific room can be calculated:

$$p = \frac{RI}{N_s} \tag{9}$$

To keep the basic reproduction number $R_0 < 1$ indicating the disease spreading in population, $R < R_0$ because susceptible persons may be exposed to more than one event. In the present analyses $R = 0.5$ was used. With this R value, at a very low number of persons, equation (9) provides high individual probabilities (p=0.5 for 2 persons and p=0.125 for 5 persons), therefore the maximum acceptable individual probability can be limited to 0.1 (corresponds to $N = 6$).

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Feedback

If you are specialist in the issues addressed in this document and you have remarks or suggestions for improvements, feel free to contact us via info@rehva.eu. Please mention 'COVID-19 interim document' as subject when you email us.

Colophon
This document was prepared by the COVID-19 Task Force of REHVA's Technology and Research Committee, based on the first version of the guidance developed in the period between March 6-15th 2020 by REHVA volunteers.

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