Point source ventilation effectiveness in infection risk-based post-COVID ventilation design

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ABSTRACT

Measurement method for ventilation effectiveness, more specifically, for contaminant removal effectiveness with a point source corresponding to infector is analysed in this study with tracer gas measurements and infection risk calculations. Ventilation effectiveness is needed in infection risk-based ventilation design to take into account air distribution methods deviating from fully mixing. Tracer gas measurements were conducted with two source location in six non-residential spaces. Ventilation effectiveness calculated based on the infection risk probability assessment for every measurement point in the room was compared with calculation from the average concentration and calculation method proposed by REHVA accounting only 50% of measurement points with highest concentration. To conduct infection risk calculation, Wells-Riley model modification providing a relation between infection risk probability and ventilation rate at fully mixing was applied together with infection risk control concept based on the basic reproduction number R_0 = 1 during pre-symptomatic infectious period. By applying the required ventilation rate at fully mixing and individual probability of infection in each measurement point, ventilation effectiveness value corresponding to given event reproduction number was solved. With the method developed, the airflow rate at fully mixing and the airflow rate with actual air distribution, calculated with ventilation effectiveness, provide the same event reproduction number. Results show considerable differences compared to calculation based on average measured concentration, which overestimated the ventilation effectiveness and underestimated design ventilation rate. The method proposed by REHVA, taking into account only 50% of measurement points with highest concentration, revealed to be conservative in all studied cases, as ventilation effectiveness values ranged in between 0.34 – 1.29 compared to 0.62 – 1.44 solved from individual risk of all measurement points. Especially in the large open plan office, REHVA method considerably overestimated the design ventilation rate while in smaller spaces all three methods provided similar results. Results indicate that ventilation effectiveness determination from tracer gas measurements with a point source is not a trivial task. Calculation method developed, utilising individual probability of infection in each measurement point can be proposed to improve prediction accuracy.

KEYWORDS

Health-based ventilation, air distribution, tracer gas, contaminant removal effectiveness, air quality index.

1 INTRODUCTION

The impact of ventilation in reducing exposure to COVID-19 and other airborne respiratory infectious diseases has been widely discussed because SARS-CoV-2 and other respiratory pathogens have been shown to be effectively transmitted through the inhalation exposure route as concluded in the review by the Lancet COVID-19 Commission (2022). As a removal mechanism, outdoor air ventilation in buildings dilutes indoor-generated air pollutants (including bioaerosols) and reduces resulting exposures to occupants. Aerosol concentration reduction by general ventilation applies for the long-range transmission, while short-range transmission occurs via face-to-face interactions in proximity to an infected person that clearly dominates at distances < 1 m (Wagner et al. 2021). WHO (2021) has developed a

roadmap to improve and ensure good indoor ventilation in the context of COVID-19 that is divided into three settings – health care, non- residential and residential spaces. In this study we focus on ventilation design in non-residential buildings, where WHO recommends 10 L/s per person minimum ventilation rate with reference to EN 16798-1:2019. This value is recommended as the highest, Category I value defined in the existing standard. Beyond existing standards, an effective air change rate of 4-6 ACH has been proposed by Allen and Ibrahim (2021) to reduce long-range airborne transmission of SARS-CoV-2 by targeting this air change rate through any combination of outdoor air ventilation, recirculated air passing through effective filter, or passage of air through portable air cleaner. Their recommendation is based on exposure science and inhalation dose risk reduction but does not distinguish spaces with low and high occupant density and is intended for large group of indoor spaces such as classrooms, retail shops, and homes if guests are visiting.

For all these recommendations it is common that no calculation method is provided for infection risk control. While L/s per person ventilation values may work both for spaces with low and high occupant density, highly different viral loads of breathing, speaking and physical activities (Buonanno et al. 2020) must be considered in the ventilation design. First steps towards infection risk-based ventilation rate calculation were taken in (Kurnitski et al. 2021) introducing a ventilation rate equation derived from Wells-Riley model modification that allows to calculate the required ventilation at given infection risk probability for fully mixing air distribution in the steady state. This is further developed in (REHVA 2022) by extending the risk control concept from the event reproduction number to full pre-symptomatic period, and by introducing ventilation effectiveness concept to take into account air distribution solutions deviating from fully mixing.

In this study we focus on the application of ventilation effectiveness and its measurement procedure with a point source corresponding to infector. Infection risk-based ventilation design method proposed in (REHVA 2022) is applied for classrooms, offices, meeting rooms and gyms where tracer gas measurements were conducted to determine ventilation effectiveness. By conducting infection risk probability assessment for every measurement point in the room, the required ventilation rate at fully mixing is increased to the value satisfying the event reproduction number and allowing to determine corresponding ventilation effectiveness value. These values are compared with ones calculated by robust and simplified method proposed in (REHVA 2022). As a result, less conservative method is proposed for accurate ventilation effectiveness calculation from tracer gas measurement results.

2 METHODS

Wells-Riley model modification providing a relation between infection risk probability and ventilation rate is applied together with infection risk control concept based on the basic reproduction number $R_0 = 1$ during pre-symptomatic infectious period. With this concept, a room specific event reproduction number and ventilation rate can be calculated applying for fully mixing air distribution. This ventilation rate needs to be adjusted with ventilation effectiveness for an actual air distribution, which measurement and application is especially studied in this paper.

2.1 Infection risk assessment

For the infection risk assessment, Wells-Riley model modification providing an explicit equation for ventilation rate in the steady state at given infection risk probability and fully mixing air distribution (Kurnitski et al. 2021) was used:

$$Q = \frac{(1-\eta_i) I q Q_b (1-\eta_s) \mathrm{D}}{\ln\left(\frac{1}{1-p}\right)} - \left(\lambda_{dep} + k + k_f + k_{UV}\right) V \quad (1)$$

where

Q outdoor air ventilation rate (m^3/h)
p probability of infection for a susceptible person (-)
q quanta emission rate per infectious person (quanta/(h pers))
Q_b volumetric breathing rate of an occupant (m^3/h), see Table 1
I number of infectious persons (-), default value $I = 1$
η_s facial mask efficiency for a susceptible person (-)
η_i facial mask efficiency for an infected person (-)
D duration of the occupancy (h)
λ_{dep} deposition onto surfaces (1/h)
k virus decay (1/h)
k_f filtration by a portable air cleaner (1/h)
k_{UV} disinfection by upper room ultraviolet germicidal irradiation UVGI (1/h)
V volume of the room (m^3)

An acceptable individual probability p for a specific room can be calculated based on the event reproduction number R, defined as the number of new disease cases divided by the number of infectors $R = N_c/I$. Considering that the number of new cases $N_c = p\, N_s$ an acceptable individual probability for a specific room can be calculated as follows:

$$p = \frac{RI}{N_s} = \frac{RI}{(N-I)(1-f_v \eta_v)} \quad (2)$$

where

R event reproduction number (-)
N_s the number of susceptible persons in the room, $N_s = N - I$ if no vaccinated/immune persons
f_v fraction of the local population who are vaccinated, $f_v = 0$ for no vaccination (-)
η_v the efficacy of the vaccine against becoming infectious, $\eta_v = 1$ for ideal protection (-)

Acceptable R during one room-occupancy event can be based on the assumption that the likelihood of infecting others (i.e. the number of infections per unit time) is approximately constant over the infectious period. In such cases, an infectious person will not infect more than one person during the infectious period:

$$\frac{R}{R_0} \cong \frac{D}{D_{inf}} \implies R \leq \frac{D}{D_{inf}} \quad when \;\; R_0 \leq 1 \quad (3)$$

where:

R event reproduction number, i.e. number of people who become infected per infectious occupant

D room occupancy period, i.e. length of time when both infectious and susceptible persons are present in the room at the same time (h)

D_{inf} the total interaction time when an infectious individual is in the vicinity of any susceptible persons during the whole pre-symptomatic infectious period (h)

R_0 basic reproduction number that describes the spread of an epidemic in the population (-)

The pre-symptomatic infectious period ends typically at the onset of symptoms, when the infectious person self-isolates at home or is otherwise 'removed' from contact with susceptible individuals. This period may last some days, on average approximately 2 days for influenza and 2½ days for SARS-CoV-2.

It is possible to simplify Equation 1 by using the Taylor approximation of an exponential $e^n \cong 1 + n$ at low doses that allow for the rewriting of Wells-Riley equation $p = 1 - e^{-n}$ as follows:

$$n \cong \frac{1}{1-p} - 1 \tag{4}$$

where

n quanta inhaled by the occupant (quanta)

Taylor approximation provides reasonable accuracy at low p values, for instance, 2.4% at p = 0.05 and 4.7% at p = 0.1. By using another approximation $1/(1-p) \cong 1 + p$ that applies if $|p| \ll 1$, Equation 1 can be rearranged as follows:

$$Q = \frac{(1-\eta_i) q Q_b (1-\eta_s) \mathrm{D} N_s}{R} - \left(\lambda_{dep} + k + k_f + k_{UV}\right) V \tag{5}$$

This equation enables us to calculate infection-risk-based ventilation rates in a simple fashion when substituting default values of quanta emission rate, breathing rate, and occupancy duration.

2.2 Ventilation effectiveness

Ventilation rate Q in Equation 5 applies at fully mixing air distribution. For an actual air distribution solution, deviating from fully mixing, the ventilation rate needs to be adjusted with ventilation effectiveness, known also as contaminant removal effectiveness (Mundt et al. 2004). Ventilation rate Q_s to be supplied by the ventilation system can be calculated as follows:

$$Q_s = \frac{Q}{\varepsilon_b} \tag{6}$$

where

Q target ventilation airflow rate for the breathing zone from equation 6 (L/s)

Q_s design ventilation airflow rate at actual air distribution solution (L/s)

ε_b point source ventilation effectiveness for the breathing zone (-)

To describe the situation with infector (=point source), a common ventilation effectiveness measurement with distributed tracer gas source describing contaminant emission from all occupants in the room, cannot be used. Thus, the point source with many possible locations in the room has to be used. It is proposed in (REHVA 2022) to calculate ventilation effectiveness as an average of two or more tracer gas measurements with different source locations. It is also proposed that concentrations of not all measurement points in the room, but only 50% of measurement points with the highest concentration are accounted for in measurement with each source location *j*:

$$\varepsilon_b^j = \frac{C_{je} - C_{jo}}{C_{jb} - C_{jo}} \quad (7)$$

$$\varepsilon_b = \frac{\sum_j \varepsilon_b^j}{m} \quad (8)$$

where

ε_b^j point source ventilation effectiveness of measurement with source location *j*
ε_b point source ventilation effectiveness for the breathing zone
C_{je} measurement *j* concentration in the extract air duct
C_{jb} measurement *j* concentration at the breathing level that is calculated as an average concentration of 50% of the measurement points having the highest concentrations
C_{j0} concentration in the supply air
m total number of measurements with different point source locations

In practice ε_b^j can be calculated from the values of the local air quality index:

$$\varepsilon_P = \frac{C_e - C_o}{C_P - C_o} \quad (9)$$

where

ε_P local air quality index at the measurement point *P*
C_P steady state concentration at the measurement point *P*

To account 50% of measurement points with the highest concentration means that ε_b^j is calculated from 50% of the points with lowest ε_P values as an average.

2.3 Calculating ventilation effectiveness from individual risk

ε_b^j calculation from 50% of measurement points is proposed by (REHVA 2022) to get a conservative value in the case of highly uneven concentration distributions. While infection risk can remarkably increase in locations with high concentration, the average concentration may underestimate it. In the following, we test how well this calculation rule holds by calculating individual infection risk in all measurement points and then summing these up to new disease cases, i.e. to event reproduction number. For the virus risk estimation at given room, the event reproduction number is solved from Equations 5 and 6:

$$R = \frac{(1-\eta_i) q Q_b (1-\eta_s) \mathrm{D} N_s}{Q_s \varepsilon_b + (\lambda_{dep} + k + k_f + k_{UV}) V} \quad (7)$$

Equation 7 is applied for every measurement point, which may represent one or more occupants, depending on the measurement grid:

$$R_i = \frac{(1-\eta_i) q Q_b (1-\eta_s) \mathrm{D} N_{s,i}}{Q_s \varepsilon_{P,i} + (\lambda_{dep} + k + k_f + k_{UV}) V} \quad (8)$$

where

R_i reproduction number for susceptible persons at the measurement location (-)
$\varepsilon_{P,i}$ is local air quality index at measurement point i (-)
$N_{s,i}$ the number of susceptible persons represented by each measurement point i,

The event reproduction number in the room is then calculated as a sum of all individual probabilities/reproduction numbers:

$$R = \sum_{i=1}^{n} R_i \quad (9)$$

In this calculation, ventilation rate Q_s needs to be solved for instance with goal seek to achieve given R value. To conduct the calculation, we use default values for virus, activity and occupancy parameters as proposed in (REHVA 2022):

- no facial cloth masks (η_s= 0, $\eta_i = 0$) and no vaccination (f_v = 0)
- surface deposition loss rate (Buonanno et al. 2020) λ_{dep} = 0.24 1/h
- virus decay (Van Doremalen et al. 2020) k = 0.63 1/h
- quanta emission rate time average values calculated based on median viral loads (Aganovic et al. 2023) of SARS-CoV-2, i.e. q = 4 quanta/(h pers) in classrooms, 6 quanta/(h pers) in offices and gyms, and 10 quanta/(h pers) in meeting rooms and restaurants
- number of infectious persons in the room I = 1 pers
- breathing rate time averaged values Q_b = 0.60 m^3/h in offices, Q_b = 0.57 m^3/h in classrooms, Q_b = 0.65 m^3/h in meeting rooms and restaurants and Q_b = 1.9 m^3/h in gyms
- occupancy duration D = 2, 6, and 9 hours in meeting rooms, classrooms, and offices, respectively
- interaction time of an infectious individual is in the vicinity of susceptible persons, including traveling, lunches, and other out-of-home activities, D_{inf} = 22.5 h in offices and 16 h in schools over 2.5 days of the pre-symptomatic infectious period

3 RESULTS

Field measurements were conducted in 6 spaces to measure local air quality index with continuous dose method. In each space, two source locations were used. Measured air quality index and source locations are shown in Figure 1 for a large teaching space of 129.5 m^2. This

teaching space with room height of 2.9 m consisted of three classrooms with movable partitions. In the measurement it was one open space for 50 persons. There were 5 supply air ceiling diffusers and 3 extract air diffusers with total outdoor ventilation rate of 520 L/s. Tracer gas measurements were conducted with 3x9 measurement points equally distributed on 1.1 m height. Additionally, 3 extract air concentration measurements were conducted from which airflow weighted average extract air concentration was calculated. Outdoor air concentration was measured from supply air duct.

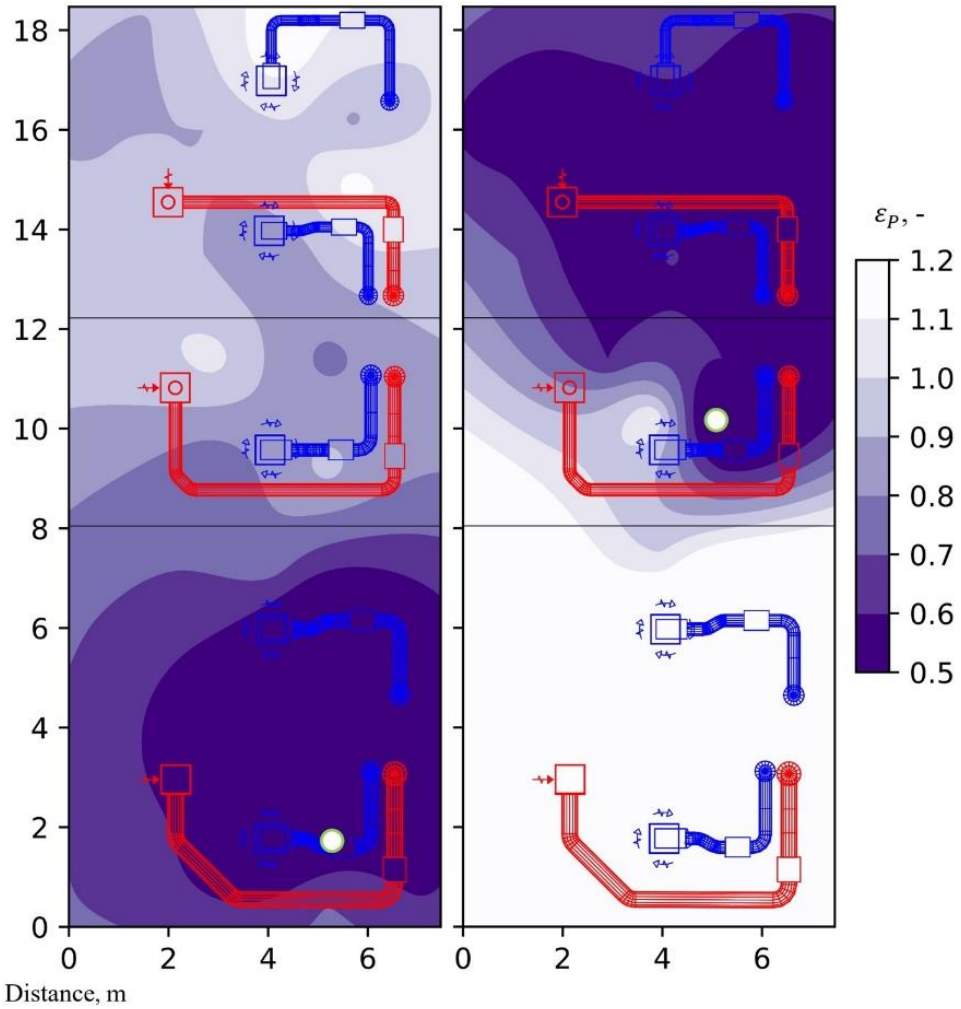

Figure 1: Local air quality index values with two locations of point source in the large teaching space of 129.5 m² with 4 L/(s m²) ventilation. Emission source is marked with green/white circle.

Another measurement example, showing the effect of extract air devices' location can be seen from 24-person meeting room in Figure 2. In this room with 52.5 m^2 floor area and 2.7 m height, 3x4 concentration measurement points were used from 1.1 m height and one measurement from extract air duct. Chilled beams with 3 L/(s m^2) ventilation rate have resulted in reasonably well-mixed condition in the case of the left source location that is far from extract air devices. In this case, local air quality index values range 0.7–1.0 in most of the room area. In the case of the right source location close to extract air devices, the situation is completely different so that high concentration zone forms close to the source and in the white area in the figure, local air quality index values range 1.5–2.

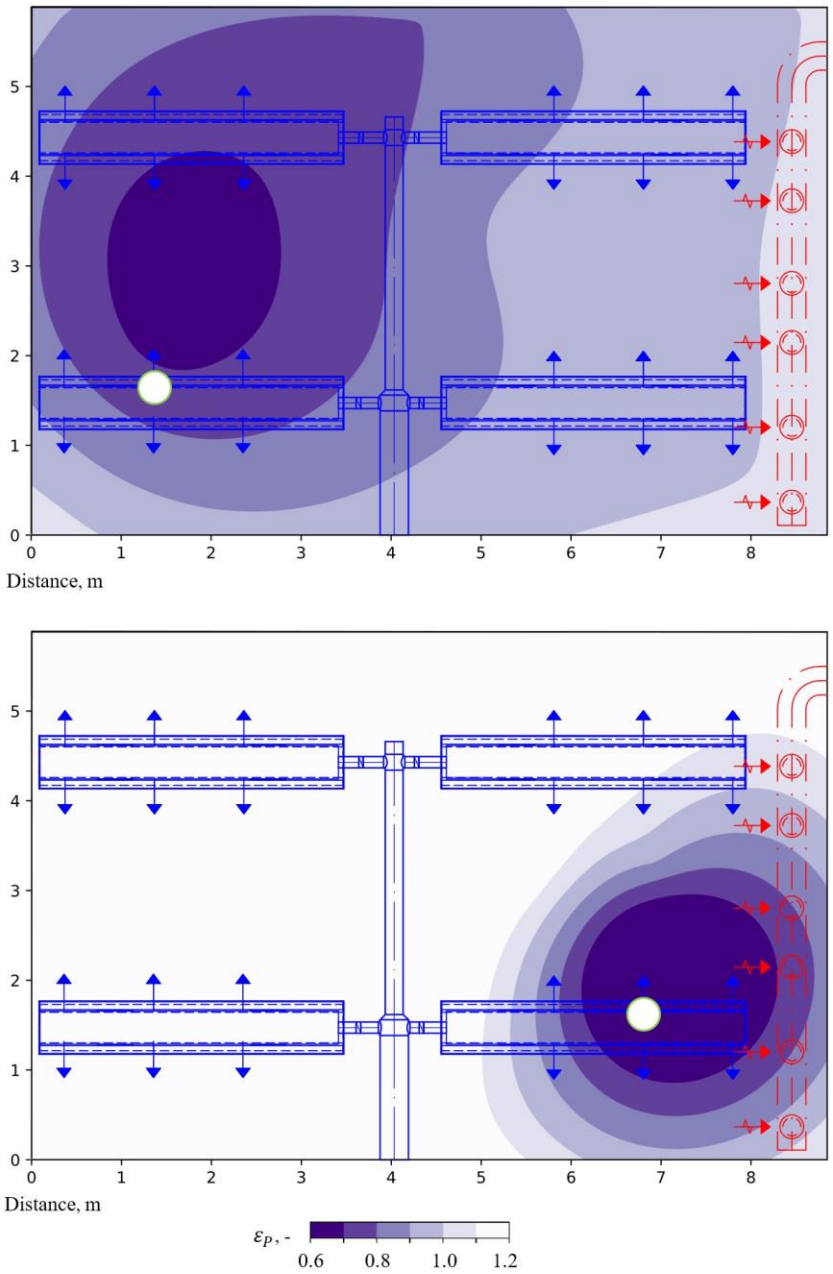

Figure 2: Local air quality index values with left and right locations of point source in the meeting room of 52.5 m² with 3.0 L/(s m²) ventilation. Emission source is marked with green/white circle.

Point source ventilation effectiveness values for all measurement cases are reported in Table 1. ε_b values were calculated with Equation 8 and 9, i.e., based on the individual probability of infection in each measurement point and resulting in design ventilation rate Q_s corresponding to specified event reproduction number (R = 0.375, 0.0889 and 0.4 in classrooms, meeting rooms and gyms, and offices respectively).

ε_b, 50% -rule represents the calculation from 50% of the lowest local air quality index values that revealed to be a conservative estimate in all cases. ε_b, *avg*, is calculated as an average from all local air quality index values. In this case, some high local values easily bias the result so that the ventilation effectiveness is considerably overestimated, leading to under sizing the ventilation rate. While in smaller rooms all three methods provide similar results, in the large open plan office, the differences are remarkable. 50% -rule strongly overestimates and average of all points strongly underestimates the required design ventilation rate.

Table 1: Point source ventilation effectiveness values and resulting design ventilation rates resulting from three calculation methods.

Room	Measurement	ε_b	ε_b, 50% -rule	ε_b, avg	Q_s, L/s	Q_s, 50% -rule, L/s	Q_s, avg, L/s
Classroom 30.5	Meas. No 1	0.99	0.92	1.00			
m^2, 13 persons	Meas. No 2	1.89	1.67	1.93			
	Average	1.44	1.29	1.46	70	78	69
	%		-10.2%	1.6%		11.4%	-1.6%
Teaching space	Meas. No 1	0.77	0.66	0.82			
129.5 m^2,	Meas. No 2	0.81	0.53	1.19			
50 persons	Average	0.79	0.59	1.01	513	683	404
	%		-24.9%	27.0%		33.2%	-21.3%
Gym 173.5 m^2,	Meas. No 1	0.56	0.46	0.66			
12 persons	Meas. No 2	1.80	1.35	2.53			
	Average	1.18	0.90	1.59	548	716	406
	%		-23.5%	35.0%		30.7%	-25.9%
Meeting room	Meas. No 1	0.90	0.83	0.91			
29.2 m^2, 6 pers.	Meas. No 2	0.96	0.87	0.97			
	Average	0.93	0.85	0.94	199	217	196
	%		-8.2%	1.4%		9.0%	-1.4%
Meeting room	Meas. No 1	0.86	0.78	0.88			
52.5 m^2, 12	Meas. No 2	1.18	1.02	1.44			
persons	Average	1.02	0.90	1.16	404	459	356
	%		-12.0%	13.4%		13.6%	-11.8%
Open plan	Meas. No 1	0.50	0.24	2.25			
office	Meas. No 2	0.74	0.45	1.19			
173 m^2, 17 pers.	Average	0.62	0.34	1.72	406	732	146
	%		-44.5%	177.2%		80.3%	-63.9%

4 CONCLUSIONS

In this study ventilation effectiveness was calculated based on the infection risk probability assessment in every measurement point in the room, that was compared with calculation from average concentration and calculation method proposed by REHVA accounting only 50% of measurement points with highest concentration. With the method developed, the airflow rate at fully mixing and the airflow rate with actual air distribution, calculated with ventilation effectiveness, provide the same event reproduction number. Results show considerable differences compared to calculation based on average measured concentration, which overestimated the ventilation effectiveness and underestimated design ventilation rate. The method proposed by REHVA, taking into account only 50% of measurement points with highest concentration, revealed to be conservative in all studied cases, as ventilation effectiveness values ranged in between 0.34 – 1.29 compared to 0.62 – 1.44 solved from individual risk of all measurement points. Especially in the large open plan office, REHVA method considerably overestimated the design ventilation rate while in smaller spaces all three methods provided similar results. Results indicate that ventilation effectiveness determination from tracer gas measurements with a point source is not a trivial task. Calculation method

developed, utilising individual probability of infection in each measurement point can be proposed to improve prediction accuracy.

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