Risk assessment of aerosols loaded with virus based on CO_2-concentration

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Introduction

Every person is emitting CO_2 and aerosols e.g. during breathing. Today aerosols are claimed to be one of the transmission ways of SARS-CoV-2 [1]. CO_2-concentrations can be measured with little effort and the correlation between the CO_2 and the aerosol concentration can be used for analytical investigations, which use the measured CO_2-concentration to calculate a likely aerosol concentration.

Background and Methods

Besides the persons as CO_2 and aerosol source, other sources as well as sinks may be important. An overview over the other sources and sinks in internal spaces can be seen in Figure 1. Apart from the person ($\dot{V}_{so,p}$) aerosols and CO_2 will also reach the room with the supply air ($\dot{V}_{sup}, c_{sup}$) and can be emitted by equipment ($\dot{V}_{so,r}$) (e.g. printer). Sinks can be the exhaust air ($\dot{V}_{exh}, c_{exh}$), deposition ($\dot{V}_{si,p}$) and the dying of the virus ($\dot{V}_{i,v}$).

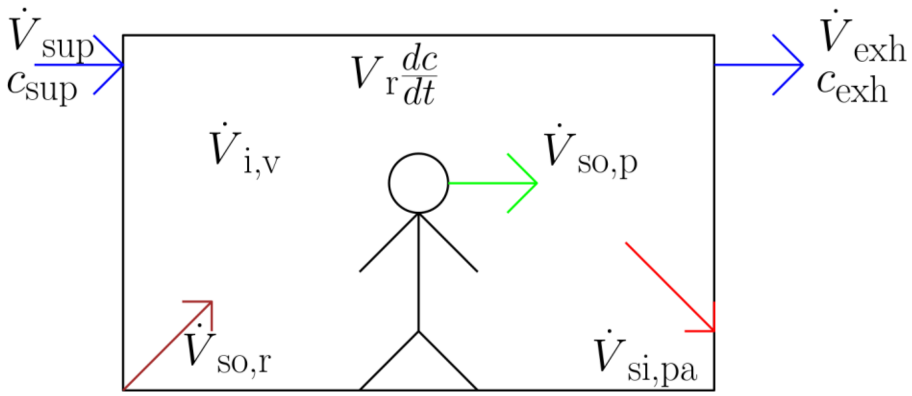

Figure 1: Overview over sources and sinks of CO_2 and aerosols in internal spaces

By means of these sources and sinks the following master equation can be set up as it may be seen in equation (1).

$$\dot{V}_{sup} \cdot c_{sup} + \dot{V}_{so,p} + \dot{V}_{so,r} - \dot{V}_{si,pa} - \dot{V}_{i,v} - \dot{V}_{exh} \cdot c_{exh} = V_r \frac{dc}{dt} \tag{1}$$

with:

$\dot{V}_{sup}$…volume flow supply air in m^3/h
c_{sup}…concentration of the contamination in the supply air
$\dot{V}_{so,p}$…volume flow of the contamination through the person
$\dot{V}_{so,r}$… volume flow of the contamination from the room
$\dot{V}_{si,pa}$…volume flow of the sink for the contamination particles/aerosols
$\dot{V}_{i,v}$…volume flow of the dying of the virus
$\dot{V}_{exh}$…volume flow of the exhaust air
c_{exh}…concentration of the contamination in the exhaust air

V_r…room volume in m³
c…concentration
t…time

In considerations of the CO_2-concentration only the volume flow of the supply air ($\dot{V}_{sup}$) as well as the concentration of the contamination in the supply air (c_{sup}), the volume flow of the exhaust air ($\dot{V}_{exh}$) as well as the concentration of the contamination in the exhaust air (c_{exh}) and the source person ($\dot{V}_{so,p}$) influence the concentration in the room. If for the concentration the difference to the outdoor air has been used, for just outdoor air supply, the part with the supply air has been omitted. Equation (1) has therefore been simplified and integrated and equation (2) has been found.

$$\Delta c_{exh,CO2}(t) = \Delta c_{0,CO2} \cdot e^{-nt} + \frac{\dot{V}_{so,CO2}}{\dot{V}}(1 - e^{-n \cdot t}) \quad (2)$$

with:
$\Delta c_{exh,CO2}(t)$…concentration CO_2 at time t in the exhaust air over the outdoor air level in ppm
$\Delta c_{0,CO2}(t)$…concentration CO_2 at time t=0h in the exhaust air over the outdoor air level in ppm
$\dot{V}_{so,CO2}$…CO_2-source in m³/h
$\dot{V}$…volume flow supply air = volume flow exhaust air in m³/h
n…air change in 1/h
t…time in h

It has to be taken into consideration, that the concentration at single points in the room can be significantly different from this value. The ventilation effectiveness (equation (3)) can be used to take this into account.

$$\varepsilon_{oz}^{c} = \frac{\Delta c_{exh}}{\Delta c_{oz}} \quad (3)$$

ε_{oz}^{c}…ventilation effectiveness in the occupied zone
Δc_{exh}…concentration of the contamination above the outdoor level in the exhaust air
Δc_{oz}… concentration of the contamination above the outdoor level in the occupied zone

For ideal mixing ventilation the concentration at all points in the room is the same and the ventilation effectiveness is therefore $\varepsilon_{oz}^{c} = 1.0$.

To set up an equation for aerosols, which may be loaded with virus, first of all some assumptions has to be made. The deposition has been calculated as product of the number of particles in the air and the ratio of particles, which have been deposited (equation (4)).

$$\dot{V}_{si,pa} = \Delta c_{particle} \cdot V_r \cdot SR \quad (4)$$

with:
$\dot{V}_{si,pa}$… volume flow of the sink for the particles/aerosols in particle/s
$\Delta c_{particle}$…concentration of particles in 1/m³

V_r...room volume in m³
SR... rate of deposition in particle/s

The aerosol source room has not been taken into consideration in the following investigations. A resuspension of virus from surfaces into the air has been of minor importance. Particles from clothing as well as skin scales have not been playing important roles for the transmission of virus, too. For the aerosol source person the following equation (5) has been set up.

$$\dot{V}_{so,p} = f \cdot ((s)(1-e) + (1-s)) \cdot \dot{V}_{so,particles,mouth/nose} \tag{5}$$

with:
$\dot{V}_{so,p}$... volume flow of the contamination through the person in particle/s
f... number of infected persons in the room
s...ratio of persons, who are wearing cloth face masks
e...efficiency of the cloth face mask
$\dot{V}_{so,particles,mouth/nose}$...emission rate of the persons through mouth and nose in particle/s

Equation (1) has therefore been changed into equation (6).

$$\dot{V}_{sup} \cdot c_{sup} + f \cdot \big((s)(1-e) + (1-s)\big) \cdot \dot{V}_{so,particles,mouth/nose} - \Delta c_{particle} \cdot V_r \cdot SR - \dot{V}_{i,v} - \dot{V}_{exh} \cdot c_{exh} = V_r \frac{dc}{dt} \tag{6}$$

Equation (6) has been solved and inserted into equation (3) and equation (7) can therefore be set up.

$$\Delta c_{particle,oz}(t) = \frac{f \cdot ((s)(1-e) + (1-s)) \cdot \dot{V}_{so,particles,mouth/nose} - \dot{V}_{i,v}}{\dot{V} \cdot \varepsilon^{c}_{oz,particle}} + \frac{1}{\varepsilon^{c}_{oz,particle}} \left(\frac{-f \cdot \big((s)(1-e) + (1-s)\big) \cdot \dot{V}_{so,particles,mouth/nose} + \dot{V}_{i,v}}{\dot{V}}\right) e^{-(nt-SR)} \tag{7}$$

If equation (2) and equation (7) has been combined in a linear equation with the boundary conditions $t = 0h$: $\frac{\Delta c_{0,Particle,oz}(t=0h)}{\varepsilon} = \frac{\Delta c_{0,Particle}}{\varepsilon}$, $\Delta c_{exh,CO2}(t = 0h) = \Delta c_{0,Co2}$ equation (8) can be set up.

$$\Delta c_{particle,oz} = \left(\frac{\left(f \cdot \big((s)(1-e) + (1-s)\big) \cdot \dot{V}_{so,particles,\frac{mouth}{nose}} - \dot{V}_{i,v}\right) \cdot \left(1 - e^{-(n-SR)t}\right)}{\varepsilon_{particle} \cdot \big(\dot{V}_{so,CO2} - \dot{V}\Delta c_{0,CO2}\big) \cdot (1 - e^{-nt})} - \frac{\dot{V}\Delta c_{0,particle} \cdot \big(1 - e^{-(n-SR)t}\big)}{\varepsilon_{particle} \cdot \big(\dot{V}_{so,CO2} - \dot{V}\Delta c_{0,CO2}\big) \cdot (1 - e^{-nt})}\right) \cdot \big(\Delta c_{CO2}(t) - \Delta c_{0,Co2}\big) + \frac{\Delta c_{0,particle}}{\varepsilon_{particle}} \tag{8}$$

For short times of use equation (8) has been simplified as it can be seen in equation (9).

Short times of usage ($\dot{V}_{i,v} = 0$V/s, $SR = 0$):

$$\Delta c_{particle,oz} = \left(\frac{\left(f \cdot \left((s)(1-e) + (1-s)\right) \cdot \dot{V}_{so,particles,mouth/nose} - \dot{V}\Delta c_{0,particle}\right)}{\varepsilon_{particle} \cdot \left(\dot{V}_{so,CO2} - \dot{V}\Delta c_{0,CO2}\right) \cdot \left(1 - e^{-nt}\right)}\right) \cdot \left(\Delta c_{CO2}(t) - \Delta c_{0,Co2}\right) + \frac{\Delta c_{0,particle}}{\varepsilon_{particle}} \quad (9)$$

Results

Application example 1:
In Figure 2 the progression of the CO_2-concentration as well as the aerosol concentration in a class room can be seen. The following boundary conditions has been used for these calculations:

- 25 persons (children 10 years)
- room volume ($V_r = 180\ \mathrm{m}^3$)
- time of usage 2 lessons (45 min) with a break of 15 min in between, where all persons leave the room
- mainly breathing ($\dot{V}_{so,particles,mouth/nose} = 140\,\frac{\mathrm{Partikel}}{\mathrm{s}}$ [2], $\dot{V}_{so,CO2} = 11{,}2\ \mathrm{l/h}$)
- ideal mixing ventilation ($\varepsilon_{particle} = 1$)
- 1 infected person, no cloth face masks ($f = 1$, $s = 0$)
- dying of the virus guided by values for influenza-virus [3]
- deposition rate guided by measurements of the HRI

Furthermore, it has been assumed that each aerosol has transported one virus [4]. At time t=0h an infected person as well as all other persons has entered the room. For the time of usage nearly no influence of the deposition as well as the dying of the virus has been found, whereas the deposition as well as the dying of the virus has been omitted in the further investigations.

Whereas for CO_2 the current concentration has been evaluated as critical, for virus the dose is important. Nevertheless, it has to be kept in mind that high virus concentration over short time may be more critical than lower concentration over a longer period.

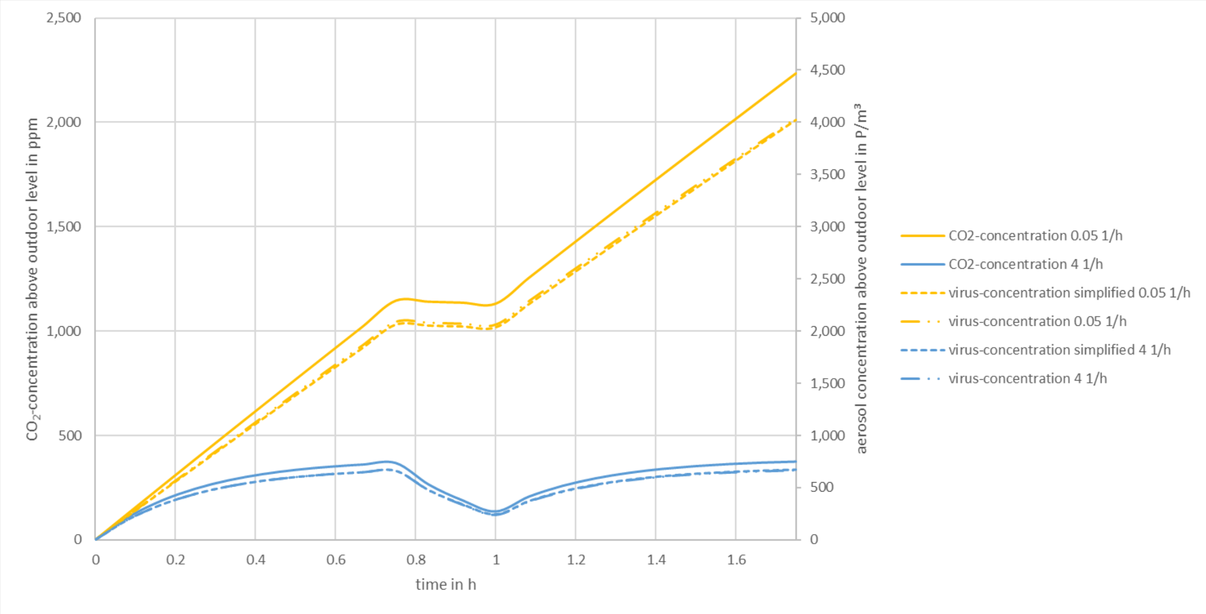

Figure 2: progression of the CO_2-concentration in a classroom during 2 lessons with a break (left axis) as well as aerosol concentration (right axis)

Application example 2:

The following considerations should be used for a simplified applicability and to formulate recommendations for action. Therefore, the exact and complex correlations have been simplified.

A boundary concentration of virus of $c_{limit} = 3.000$ virus has been used, which a person can breath until it has been assumed probable that he/she has been infected [5]. If this critical dose has been reached it is suggested to leave the room.

The following scenario has been used: An infected person has stayed in a room for a longer time. The CO_2-concentration as well as the aerosol-concentration has reached steady state. Another person (non-infected) has entered the room at time t=0h. Depending on the volume flow per person this person can stay a certain time in the room until the boundary concentration of $c_{limit} = 3.000$ virus has been inhaled.

The volume flow per persons has been estimated regarding DIN EN 16798-1 [6]. In table 1, these volume flows can be found. The compliance with the specific volume flow can be checked with a ventilation traffic light, which is based on the CO_2-concentration.

Table 1: necessary outdoor air supply regarding DIN EN 16798-1 [6] (used values printed in bold)

	Raise of concentration above the outdoor level (450 ppm) in ppm	volume flow in $m^3/(hPer)$ (low-emission building, $10m^2$ per person)	volume flow to comply with the limit for the CO_2-concentration in $m^3/(hPer)$	color of the ventilation traffic light
IDA 1	350	**72**	43	green
IDA 2	550	**32.2**	27	green
IDA 3	1050	**18.4**	14	yellow
IDA 4	1550	**14.4**	10	red

To calculate the maximal duration of stay equation (10) has been used.

$$t_{max} = \frac{c_{limit} \cdot \dot{V}_{sup}}{\dot{V}_{so,particles} \cdot \dot{V}_{inhal}} \cdot n_{persons} \qquad (10)$$

with:

t_{max}... maximal duration of stay in h

c_{limit}...limit dose of virus $c_{limit} = 3.000$ virus

$\dot{V}_{sup}$... person-related outdoor air supply in $m^3/(h \cdot Per)$

$\dot{V}_{so,particles}$... particle emission rate through the infected person in particle/s

$\dot{V}_{inhal}$... inhaled volume flow in m^3/h

$n_{persons}$...number of persons in the room

The inhaled volume flow is thereby depending on the activity and can be found in table 2.

Table 2: air requirement for inhalation for different activities

activity	degree of activity	required volume flow for breathing in m^3/h
reading or writing	I	0.375
extremely easy physical activity (standing or sitting)	II	0.575
physical activity	III	0.75

For a case in an office or a school degree of activity I has been used. The results of these investigations can be found in Figure 3. The diagram has been based on the assumption that only the infected person is in the room. For every further person, who is not infected, entering the room maximal duration of stay can be multiplied with the number of person, because it has been supposed that the volume flow has been adjusted to a constant CO_2-concentration.

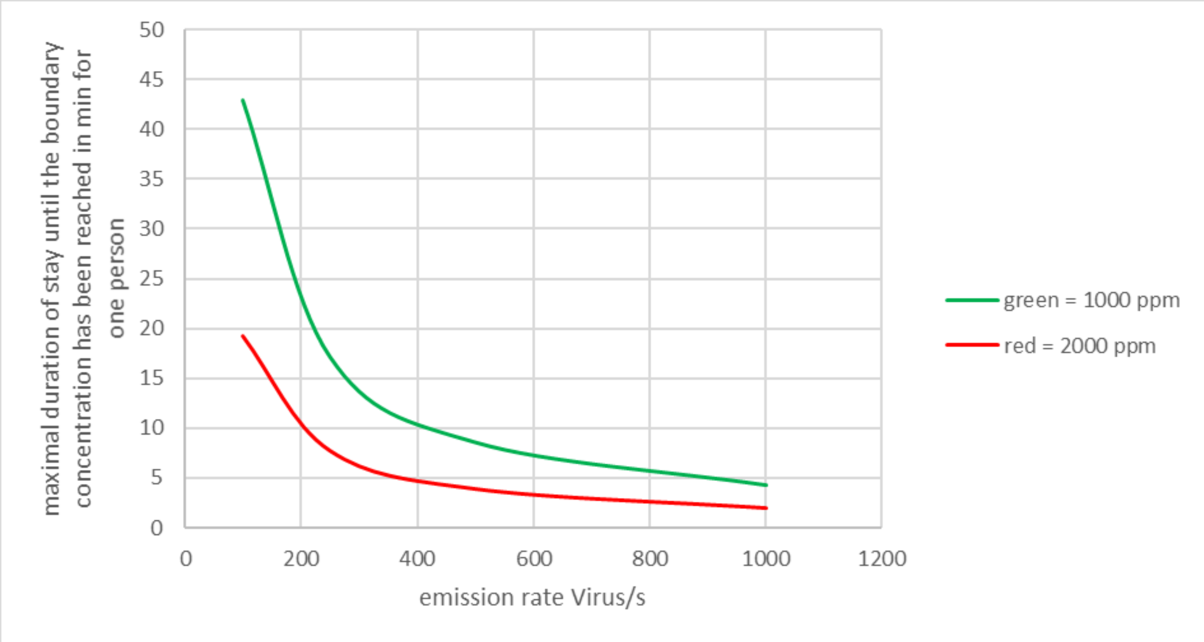

Figure 3: maximal duration of stay for one person in a room with one infected person

An infected person can stay in a room with a green ventilation traffic light for a little more than 30 minutes, if he/she is breathing ($\dot{V}_{so,particle} = 140\ \mathrm{Viren/s}$ [2]) until he/she has inhaled 3,000 virus. It has to be kept in mind that the person is already infected, so this would be a theoretical case. Another person entering the room would lead to an increase of the outdoor air supply and therefore the maximal duration of stay would be 60 min. If the volume flow is lower (ventilation traffic light is red) both persons would have inhaled the boundary concentration of virus after about 30 min already.

Summary and Discussion

The results of these investigations have shown that CO_2 is a good indicator for the efficiency of the ventilation system and is related to the outdoor air supply. The dying of the virus as well as the deposition play a minor role for aerosols, because of the short duration of stay until the boundary concentration has been inhaled.

With a high air change rate, low CO_2-concentrations can be reached as well as low aerosol concentrations (see Figure 2). The lower the concentration of aerosols, the lower the dose of aerosols a person in the room is going to inhale and the infection risk as well. For given CO_2-concentrations (table 1) the equations has been applied to calculate the maximum duration of stay in internal spaces (Figure 3). For these investigations different simplifications has been used, which should be taken into consideration if interpreting the results. First of all, a steady CO_2-concentration as well as aerosol concentration has been assumed. If another person enters, the room the risk will therefore will be underestimated at the beginning, because the volume flow will change relatively fast, but the concentration will need a longer time to decrease. Nevertheless for all investigations it has been supposed that a high dose for a short time is as critical as a low dose for a longer period and dying of virus as well as deposition has been omitted. The gained results, with the taken assumptions (boundary concentration, one virus per aerosol), can be seen as a first approximation to give same recommendations for action.

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