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Article

Physical analysis of SARS-CoV-2 routes: from primary production and emissions to exposures and COVID-19 infection

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Abstract:

Measures in the SARS-CoV-2 pandemic were based on rough ideas regarding transmission routes of pathogens. Quantified models of physical transmission routes are mostly lacking, a gap to be filled. Vaccines and medicines, important, are not studied here. We first survey main routes, from primary production in the alveoli and intestines to emissions, environmental routes, to exposure and alveolar infection. Next, specific routes are modelled, mostly at a preliminary state, open to systematic improvement. Starting from a standardized emitter, modelling results show extreme differences in potential exposure, in a range covering up to 4 orders of magnitude. The outcomes are pathogen-specific, already different between SARS-CoV-2 and influenza. Extreme exposures may result in smaller spaces; with lower ventilation rates; with a high density of emitting persons per m^3; who stay there for several hours; and visitors staying more than a few minutes. In spaces where a build-up of concentrations is low, exposures are low, lowest in open air situations. A main conclusion for the next pandemic is that a quantified model can give strong guidance on where measures are primarily due. For SARS-CoV-2, ventilation can be improved short-term. Longer-term, effective ventilation rules and adaptation of buildings may reduce high exposures substantially.

Keywords: SARS-CoV-2; COVID-19; Virions Mass Balance; Spatial modelling of concentrations; Human Exposure; Substance Flow Analysis

1. Introduction on SARS-CoV-2 virion stocks and flows[1]

1.1. The aim of modelling environmental transmission routes

Age-old knowledge is used to control epidemics. Prime measures include quarantine (*quaranta giorni*), social distancing, mask wearing, and direct physical contact avoidance. They have all been applied since the 14th century, as a public reaction to a public danger [1]. Neither the Black Death nor SARS-CoV-2 (short: SARS-2) have been contained, however. With modern knowledge, modelling, and data, a more detailed and quantified picture of infection routes can be developed, distinguishing the relative risk levels of different circumstances. They are specified here for SARS-2, the cause of COVID-19 pneumonia. On that basis, more focused preventive measures may be developed. In between virology and medicine at a micro level and the pandemic at the macro-level of epidemiology, there must always be a physical route bringing the SARS-2 virions from infected persons to still healthy persons. A toxic infection must have a source and a route, its fate, so does viral infection.

The WHO advice to the public regarding SARS-2[2] includes 1-m physical distancing, wearing a mask, avoiding crowds, cleaning your hands, and coughing into a bent elbow

[1] See the README file for Supporting Information, combined in one text and one spreadsheet.

[2] https://www.who.int/emergencies/diseases/novel-coronavirus-2019/advice-for-public/when-and-how-to-use-masks

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or tissue. Quantified models for supporting these measures for SARS-2, or establishing their relative importance, are fully absent. At a case level, direct hand contact or fomites transmission leading to COVID-19 pneumonia has never been established. But how strong is that sort of indirect proof without analytic modelling? Current lack of knowledge also shows in diverging advises by country CDCs. The US-CDC advised 'have your Thanksgiving party outside', while at the same time most European CDCs advised on closing parks, with in many countries police control. Terraces and sports fields were closed in many European countries, while US cities closed roads to traffic to create space for outside dining. The analysis of such potential measures is not a subject of this study, though gently touching on them in the conclusions.

Before endeavoring in applied modelling, we show major gaps in knowledge ideally to be filled. The physical model outcomes have two related functions. First, they connect medicine and virology on the one hand with epidemiology and health science on the other. Next, they form a basis for citizens and governments to evaluate measures, combining relative risks with options for measures, in their broader juridical-administrative and socio-economic contexts.

The *goals* of this study are:

- to develop the conceptual framework model for the quantified analysis of the SARS-2 virion flows from primary production to exposure and potential infection

-to preliminary fill in quantified sub-models

-to specify gaps in models and data remaining.

Our subject is not just a historical issue. The SARS-2 virus is here to stay, like the common cold and influenza did before, and new human viruses will come. The encompassing physical analysis must form the foundations of its sustainability analysis, placing measures in perspective.

1.2. The nature of the study

An overall model from SARS-2 production and emission to comparative exposures and potential infection does not exist. Partial models do not cover the full field. Here we first fill in the overall conceptual model, the modelling architecture. Next, sub-models fill in the sequences from primary production of SARS-2 virions to emissions; from emissions covering the environmental routes to exposures; and from exposure to COVID-1 infection. Available partial models are combined and developed into more coherent models where possible, with gaps shown. Quantification is possible to some extent regarding the steps from primary production to airborne emissions, in the spread sheet model we develop. Though substantially assumption-based, outcomes can somewhat be aligned with empirical data. Quantified modelling is possible for the stage from airborne emissions to concentrations and exposures, using available partial models and data from other domains. For fluid and solid flows there are only incidental and partial measurements, showing comparative orders of magnitude. The stage from exposure to illness cannot be filled in quantitively, due to the basic lack of partial models and data. For all routes in the overall conceptual model, an outline of specific modelling requirements is made.

A third task could have been the independent validation of the models. As we used available knowledge extensively already, this would require new data gathering, a prime task to come for science and society. There has not been any primary data gathering in the project.

1.3. To which scientific domain does this subject belong?

The subject has inputs from virology and cell biology and physiology. But it does not belong to either of these subjects. There is also a link to epidemiology and more general to health sciences, but it certainly is not part them. Between emissions and exposures several applied technical sciences have links, such as building sciences, ventilation sciences, behavioral sciences, and ultimately ethics and normative political science. All of them have various specialized and more general journals. Nowhere would our physical stocks and flows subject fit in. The scientific development of this

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interface is broadly seen as a necessity. The development of such a framework is advocated in [2] (ES&T, with 213 references). So do [3] (acsNANO, 110 refs) and [4] (Focus on Fluids, 283 refs) who focus directly on their specialized domains. Later [5] (Science, 14 refs, with 39 authors) advocated this subject but with a focus on all airborne infections together, not SARS-2-specific, and on ventilation as a measure only.

Industrial ecology may be defined in different ways. As *the science of the material basis of the economy*, this subject would not be part, see in this sense Wikipedia, with broad references there[3]. Taken as *the science of the physical aspects of society* it might be part, covering emissions and exposures more directly. We take that quite usual position. The broader domain is environmental sciences. The physical analysis is core in the broader sustainability analysis of options.

Main methods of industrial ecology are relevant. First, there is the analogy with processes analysis in Life Cycle Assessment (LCA). The basic sequence there is, next to functional aspects, that substances are taken in or created, partially emitted, diluted/concentrated transformed/broken down in the environment, and next having their impacts, including health effects. Several studies cover biotic emissions as well, as in cows emitting methane, for example [6, 7].

Next, in the toxicity analysis of airborne Particulate Matter (PM) there has been a shift from PM10, which includes smaller SARS-2 containing droplets; to PM2.5, still smaller airborne evaporating droplets, here with SARS-2 virions; to UFPs [8], the often most harmful Ultra Fine Particles (<100nm), in the size order of single SARS-2 virions (140nm, 100nm without spikes). There is a direct link with Substance Flow Analysis (SFA). It can specify stocks resulting from flows, essential for specifying environmental concentrations and then potential exposures. Mass balances must hold, also for short-lived toxics like virions.

The routes from primary production, different emission routes, different environmental fate routes, and from there to exposures and potential infections seems well-linked to the subject of environmental science, including industrial ecology.

2. Method

2.1. Gaps in SARS-2 knowledge on physical flows surveyed and partially filled

The core task regards the modelling of the physical routes from primary production and emissions to exposures and alveolar infections, first conceptually and where possible quantified. Even the conceptual model is fully lacking now in the literature, let alone with all sub-models filled in. Even the quantification of primary production in the alveoli is lacking; the route from alveoli to alveolar sacs and higher airways has not been modelled, and the link to the highly frequent infection of the intestines is absent. The reverse route of particles into the respiratory systems has been well-investigated in the literature, but not for COVID-19 pneumonia but for administering medicines to the deep level, up to below UFP-size, for their effective alveolar application. Also data on flows and concentrations are dearly lacking. At emission, most analyses take only emitted droplets into account, not linked to primary production and transport mechanisms. Gravity-based separation apparatus can gather droplets of over 1000nm (at best over 500nm) while the virions (140nm) and small virion containing clusters leave in their exhaust, unmeasured. Quantified single virion measurements are in development, not yet standardized. Anal swabs show the presence of viable virions, but not quantified emissions.

The environmental routes following airborne, fluid, and solid emissions have not been modelled, as for showing comparative concentrations and exposures. Finally, after human exposure there is no physical model in the literature of how the alveoli are reached, resulting in the COVID-19 pneumonia.

How to deal with this dire situation? We start with the overall conceptual model and fill it in, quantified where possible, even if only as a tentative start.

[3] https://en.wikipedia.org/wiki/Industrial_Ecology

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2.2. Overall model design

The overall model structure has three stages, see the three blocks in Figure 1, leading to airborne and fluid emissions from the airways and solid emissions from the intestines. These next have environmental routes leading to five different types of exposure. Small droplets evaporate, joining the directly airborne emissions. Closed and open spaces differ in modelling requirements. In closed spaces, concentration builds-up, restricted by virion decay and ventilation, leading to exposure flow 1. Outside there is wind transport and diffusion, with exposure flow 2. Larger droplets may lead to contact exposures, as does solid stool, leading to exposure flows 3, 4 and 5.

Virions in exposures must have been produced and must not have gone astray on the way there: mass balances must hold, the basic SFA-principle. The implementation of sub-models can be aided by lab research and by substantial partial knowledge, not just from SARS-CoV-2 times, as for example on the movement of exhales.

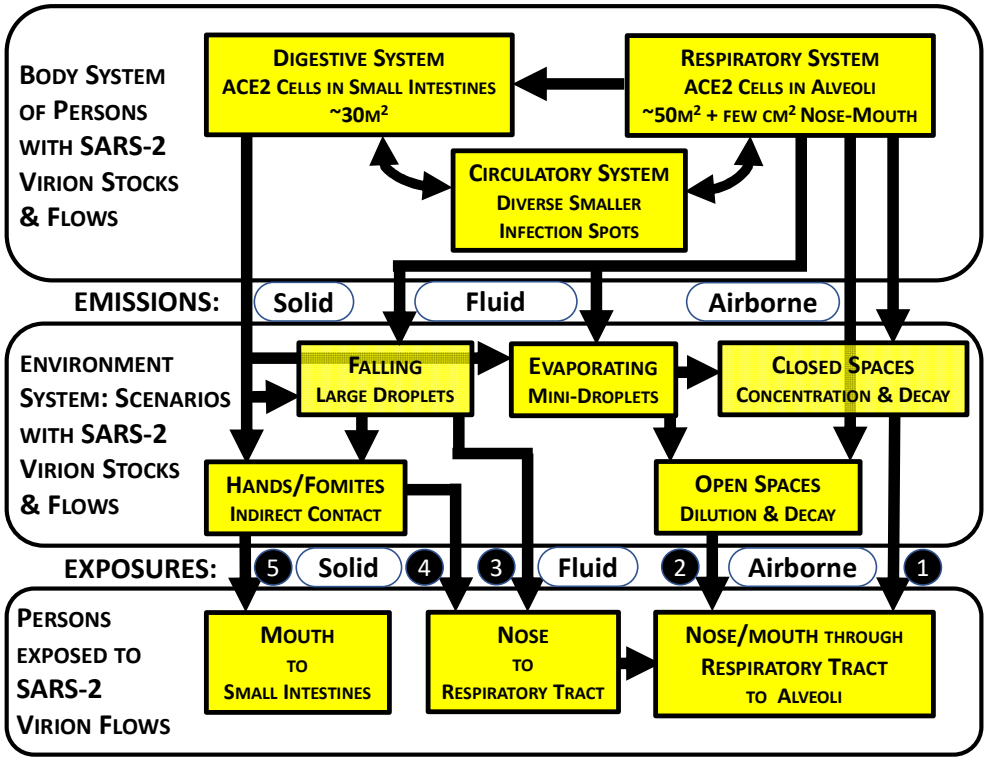

Figure 1. Mass flows of SARS-2: productions, emissions, transformations, and exposures

2.3. Design strategy

The core aim to arrive at comparative results regarding infection risk requires reasoned standardization in modelling design. The items are surveyed pointwise.

- Though there is extreme variability in emissions per person and between persons, a standard emitting person is at the core of all exposure quantification.
- The standard person is a normal person at rest, with a standard inhalation-exhalation frequency and time, set at 3.6 seconds per tidal breath and a volume of 0.5 liter, resulting in 0.5m^3 exhale per hour.

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- The standard person is not yet seriously ill and hospitalized.
- The emission in a closed space is set 1 emitting person per 20m^3.
- Ventilation has been standardized to the only reliable mode: well-mixed ventilation, following [9], applying a broad range of ventilation rates.
- Outside ventilation is based on a standard very low wind speed, 1m/s.
- The situations discerned cover all closed spaces and all open spaces, but not half open spaces such as stadiums.
- The exposure is specified for one person in all situations. The actual number of persons exposed links to epidemiological analysis, not modelled in this paper.
- Room modelling is non-linear but is linear homogeneous, allowing for easy scaling to different numbers and assumptions.
- Specific prevention measures have not been included in the models, as the goal is to indicate relative risk in different situations, to help guide the development and choice of measures.
- Exposures are quantified for a standard inhaling person, a healthy person at rest with standard tidal flows in breathing, the same as the emitting person.
- The relation between exposure, infection, and illness has not been modelled as standardization was not possible, due to extreme variability and uncertainty. Model requirements and some indications of mechanisms have been specified.
- For most values, a sensitivity analysis has been made to show the effect of different numbers and assumptions.

More details and references are in the three sections per modelling stage discerned.

The full model structure and the linked sub-models have all been newly constructed. As the current SARS-2 pandemic may still last for longer, and as there will be more epidemics and pandemics, the subject might develop into a new subdomain: Viral Substance Flow Analysis. The three main stages are in one chapter each (Ch3, Ch4 and Ch5), followed by the chapter on application to specific situations (Ch6), and the conclusions (Ch7).

3. Models from primary production to emissions

3.1. Available partial models and data, and gaps

SARS-2 (and SARS-1 and MERS similarly) can only reproduce in cells with ACE2 receptors. Most are in the alveoli, the gas-blood exchange chambers in the lungs, with around 50m^2 surface [10], and in the small intestines, with a food related exchange surface to blood of around 30m^2 [11]. These are the two main factories for primary SARS-2 production, ultimately resulting in emissions. Open to external infection are also the ACE2-cells in the nose and mouth and throat, in the cm^2 to dm^2 domain, 3 orders of magnitude smaller than the alveoli. Some more are in diverse places inside the body with small arteries, such as in heart muscles, kidneys, brain, and some sweat glands, see the detailed analysis in [12] and with some additions [13] pp.229-231, and for bone marrow [14]. There a secondary in-body infection may occur. Virions from the alveoli and small intestines may enter the blood stream. Blood flows, the circulatory system, link all possibly infected tissues, including the alveoli and small intestines themselves. Positive virions tests in the airways are closely linked to positive tests in stool. The latter may last for weeks and months after the end of the alveolar infection [15-18]. SARS-2 readily reproduces in the gut enterocytes as well [19, 20]. Viable virions have been proven present in stool [21, 22]. Quantified data on stool emissions are lacking, however. Next, PCR-tests in sewers give quantified results, see early [23] and many later. They never involved viable virions. Blood-based emissions and exposures have not been documented. Sweat glands might be a research candidate for relevant emissions [24], without any quantification yet, and probably not semen [25].

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3.2. *Stocks and flows detailed*

SARS-2 virion production in Covid-19 persons, the primary flow, is from infected pneumocytes, the stock. As the production infects other cells newly, the stock and the flows increase. This increase is halted when SARS-2-specific defenses or medicines become active.

In SARS-2-infected persons the outflow in stool may be substantial as indicated by PCR tests on stool, comparable to swabs in their nose and throat, see [22], with viable virions in stool possibly emitting. We treat these PCR-outcomes for an extreme sensitivity analysis.

3.3. *Dynamics of respiratory stocks and flows*

In lab-based replication using defenseless Vero E6 cells, production and emission starts within hours, possibly infecting new cells [26], and halts at around 14 hours at cell death. In humans there are varying estimates of the period of exposure till replication with positive PCR test, from asymptomatic illness to symptomatic illness, hospitalization, ICU, and death. Up to half of positive tests remain asymptomatic, especially with younger persons, see the survey analysis in [27]. We developed a growth model that roughly fits these time periods, see the spreadsheet-model in SI-W1, and see SI-T1 and SI-T2 for nomenclature and assumptions. Before onset of specific defenses there is exponential growth in in-body stocks, primary production, and emissions. The growth rate is set at around 2.5% per hour, doubling in slightly over a day.

The lowest starting exposure is in Day 1. Higher exposures may start the infection, for example at 'Day 10', then with a much shorter time to possible symptomatic illness. The time between exposure and symptomatic illness is virtually always less than 14 days [28] or 10 days [29]. There is a strong relation between high (PCR-based) virion tests and later severeness of illness [30], in line with this illness-development model.

The production in the alveoli is in the two flattened-cells thick layer between air and blood. Each pneumocyte cell has a thickness between 100 and 200nm, the size of a SARS-2 virion, while the total blood-air barrier has a thickness between 500 and 700nm. The produced virions leave partly towards the blood, in unknown quantities. Towards air, the virions first pass the surfactant-rich watery layer, <100nm thick but with substantial local variation [31] and similar [32], and [33] on rats. The alveolar sacs (~20 alveoli per sac) are connected to the alveolar ducts and from there to the lower and upper airways [34]. Some outside air may flow into the alveoli with each tidal breath, and virions-infected air goes into the airways at exhalation. Alveoli and airways are never empty (Residual Volume >1L; inhale at rest ~0.5L), see details in [35]. So, a part of virions leaving the alveoli returns to other alveoli, as self-infection. In the smallest airways virions may become small watery droplets at inhalation when the small airways open after collapse by deep exhalation [36], with the water composition investigated for medical reasons [37]. All airways are covered with epithelial cells where the virions can be caught in mucus, most of them being deactivated there. Mucus with virions and virion parts is transported by the epithelial cells to the throat (~20cm/hour) and mostly swallowed. Mucal droplets can be created in the airways and exhaled by breathing, singing, and speaking, and are most forcefully exhaled in cough/sneeze bursts. Shares in virion quantities are lacking, as are mass balances. See Figure 2, and a general description of the respiratory system in [38].

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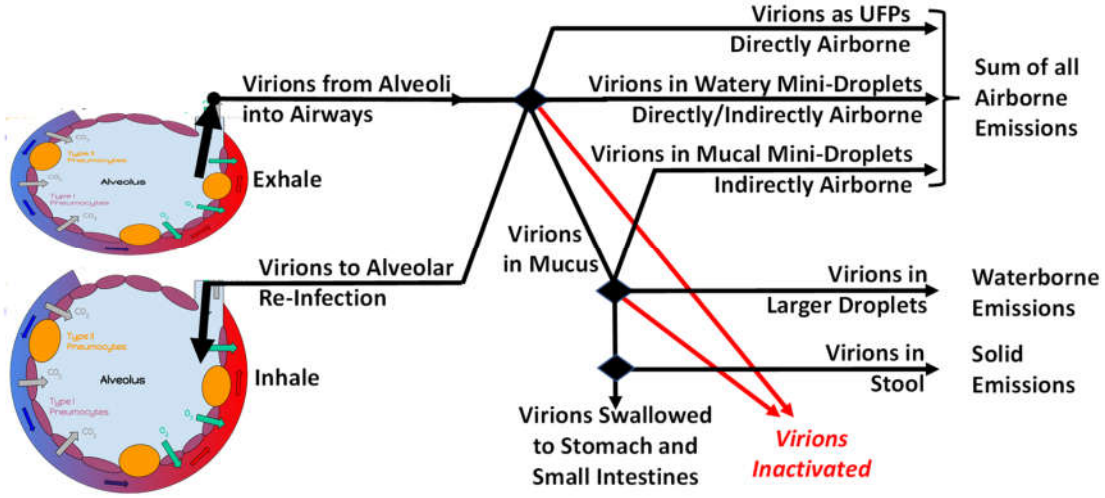
Figure 2. SARS-2 virions flows: from primary alveolar production to emissions



3.4. Standard emitting person quantified

The reference person has an infection level of around Day 17, set at emitting 100 000 virions per hour, 100 virions per exhale, and remains in public. Its emission will rise till the onset of specific defenses. Exhales number between 6000 and 600 000 thousand virions per hour, PCR-based, in a group of partly hospitalized patients [39]. Our Standard Person is in the upper-middle level there. At 'Day 17' infection level, ~0.2% of the alveoli would have been infected, ~1m^2. That will constitute a severe burden for the body, imagine the same surface of infected skin.

4. Modelling environmental concentrations and exposures: main routes in closed and open spaces

4.1. Available partial models and data, and gaps

Empirical measurement of single viable airborne SARS-2 virions is very seldom. After SARS-1 a first bubbling-based air filtration system has been developed [40]. Viable airborne SARS-1 virions were measured already in Toronto [41], but not yet quantified. Newer measurement apparatus has been developed [42]. The quantification for SARS-2 is by [43], Table 2, focused on particles below 500nm, see his in-hospital measurement in SI-W8. Quantified measurements, also for droplets, remain by necessity highly diverging due to many confounding circumstances and lack of standardization (also personal communication with John Lednicky). See the comparison with our mass balance-based modelling outcomes in SI-W8.

SARS-2 virions decay in the environment, in closed spaces with HalfLifes estimated between 1 and 3 hours and in open spaces down to 15 minutes [44] and similar [45]. In watery suspension in lab situations with droplets of >2000nm virion decay may be much slower [46].

Models for open spaces have been developed for non-persistent micro-pollutants at a meso-level, with ozone formation and destruction as one example [47]. Large scale vertical mixing and time of day play a major role there. There is substantial partial analysis for example on pedestrian level exposure by UFPs from combustion engines [48], related to cardio-pulmonary health effects. The scale level is still that of city regions, however, way beyond where dispersion of SARS-2 virions may be relevant.

There is some empirical measurement of dilution at shorter distances. Peak concentrations of gas leaks from storage tanks at distances up to 180 meters, with different wind speeds are given in [49]. Their data indicate a constant dilution

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per distance, independent of wind speed. However, the spatial level relevant for SARS-2 is in the meter domain, up to 15 meters at most, as there is no concentration build-up and always some transport and dispersion.
The gap in quantified outside modelling and measurement of SARS-2 virions is clear: it does not exist. We fill in the gap with several modelling approaches.

4.2. Closed and open spaces

Closed spaces and open spaces cover all environments. In closed spaces all three types of emission occur, airborne, watery, and solid, and all five types of exposure, see flows 1 to 5 in Figure 1. Airborne emissions cover single virions and droplet-nuclei with virions. Droplet-nuclei result from fast evaporation of small droplets before falling, with the non-water part of the mucus-based droplet around 3% [32], p.6. Larger droplets may infect the nose directly or by first passing to fomites. Stool and stool-droplet fomites may be brought to the nose for infection and to the mouth, then swallowed towards the intestines.
Infections in China were mostly contained. So, with rare single new cases outside Hubei, individual outbreaks could well be traced, with analysis of the location of secondary infection of a new case [50]. Of the 1245 cases covered, just one infection was probably not indoors, with only one person secondarily infected then. Modelling outside exposures has serious gaps. Fluid and solid exposures have mostly rudimentary conceptual modelling only, with limited and mostly just partial quantification.

4.3. Closed spaces airborne concentrations (time dependent)

For modelling, a closed space is set at 1 emitting person per 20m^3 (5 per 100m^2 equivalent) emissions. With 5 persons per 100m^3 at 150cm distance twelve persons fit in easily; at 1 meter (examples: well-filled restaurant or bar, birthday party) 30 persons would fit in. The continuing inflow, itself exponentially rising, is countered by two concentration-dependent exponential outflows: decay and ventilation. Standard decay is set at 120 minutes HalfLife, with a sensitivity analysis at 60 and 120 minutes (and for outside spaces also 15 and 30 minutes). Ventilation rates cover a broad range from 1 up to 60. Concentrations increase in time, with ventilation dominant over decay long-term, see Figure 3. The model description is in SI-T3 and the stocks and concentrations in SI-W3 to SI-W7, the exposures in SI-W9 to SI-W13, and the stepwise spreadsheet, for easy sensitivity analysis, in SI-W16. The in-house developed new model combines the three exponential mechanisms, with the well-mixed ventilation part following US-CDC [9].
The survey by [51] indicates the importance of ventilation for infection prevention also for SARS-CoV-2 but lacks mass balancing for inflows, decay, and ventilation. Ventilation rates per hour (VRs, US: Air Change rates per Hour, ACHs) cannot well be specified for specific situations. At low ventilation rates mixing may be limited, with then locally higher concentrations, most extreme if inversion layers evolve [52]. For larger spaces, flow ventilation may be more efficient, iff well-designed and executed. This holds similar for complex formed places with high person-density, as in transport, see SI-W2 on airplanes. In spaces with only passive natural ventilation, it is the density (humidity-temperature) difference between inside and outside air that drives the ventilation, aided by wind kinetics. Natural ventilation can be close to zero, even if windows are opened, which they are often not. Air filtration can be equivalent to ventilation, saving on energy costs. Air conditioning may cool or heat but normally does not ventilate or filter virions, and may transport them to connected rooms [53]. A ventilation rate of 0.1 is quite common in private housing. School classrooms investigated in England showed VRs down to zero (new schools, all windows closed) and VR0.84 on average [54], though norms are in the order of VR5. Private sleeping rooms in China vary depending on outside temperature and window closing. If closed, the median VR tends below VR0.45 [55]. For the more infectious SARS-1 [56] found for hospital situations that VRs below 25 still gave a serious chance of infection. Only VRs above 250 (!) proved to be risk-free for long-duration inhalation.

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Our model data cover VRs from 0.1 to 60 (40 well possible in cars [57]. The resulting range of room concentrations is wide. For VR0.1 the concentrations at minute 60 (one hour) is 4036 virions/m^3 and at minute 720 (12 hours) becomes 14052. For VR20 these numbers are 248 virions/m^3 at t60 and 326 virions/m^3 at t720. See the full results in SI-W5, also for different HalfLifes. Shifting HalfLife from 120 to 180 minutes shows substantially higher concentrations.

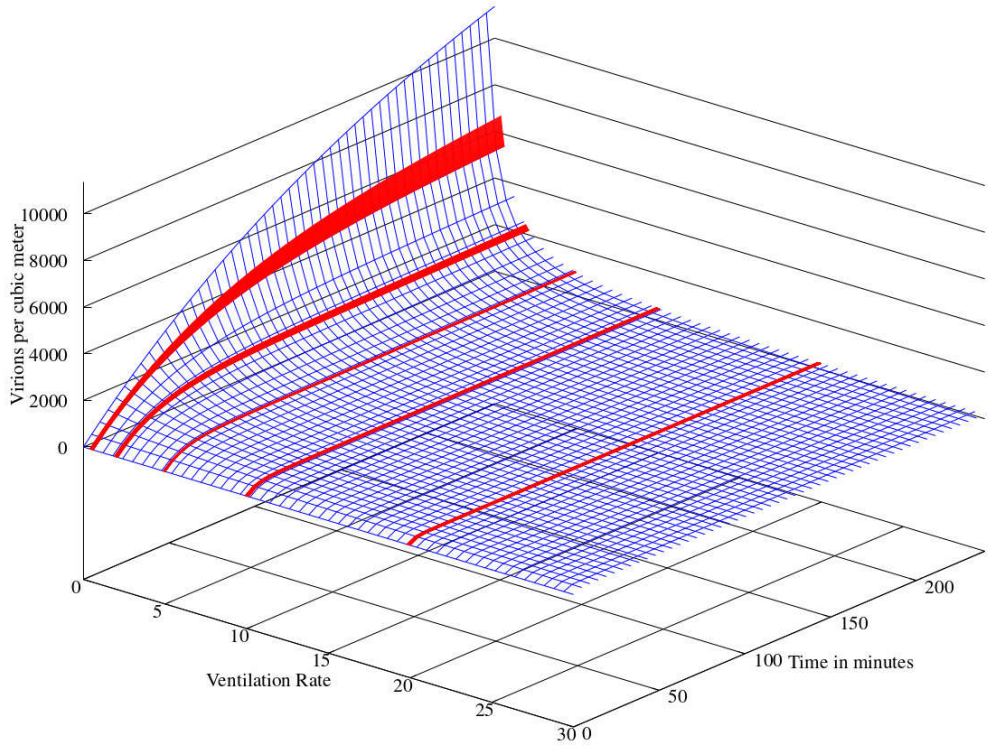

Figure 3. Concentrations rising in time with different ventilation rates
(red lines: VR0.1; VR2; VR5; VR10; VR20)

4.4. Closed spaces airborne exposures (time & duration dependent)

The concentrations in closed spaces build up in time. Duration of stay over the concentration determines the exposure. Staying periods are 1, 5, 15, and 120 minutes, while entering at minute 1, 60, 240, 480, 600, 1320, and 2760, covering two full days after 2 hours stay. Entering a sick room and staying there for 6, 12, 24 hours and 48 hours is added as relevant for a long-term care facility. Following [44], we use exposure with 350 virions as indication of probable infection, 100 as a minimum, and above 1000 as a high chance of infection.

Exposures differ widely, see the results tables in SI-W14 and SI-W15. At a one-minute stay, infectious exposure is only reached in fully non-ventilated rooms, entering 24 hours after the infected person, for HL120 (the standard) and HL180. The 5 minutes stay at HL120 may reach infection with VR0.1, entering at minute 240. With higher VRs the entering time for relevant infection recedes, to minute 1320 for VR0.5 and minute 2760 for VR1. At higher VRs exposures are too low for infection.

The 15 minutes stay leads to infectious exposure when entering at minute 60 already, also for other ventilation rates (except HalfLife 15 minutes, relevant outside). That risk drops starting from VR2 and VR5, with hardly risks beyond VR10.

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The 120 minutes stay gives high exposures. It requires the still unusual ventilation rate of at least VR20 to reduce the exposure below infection level. At VR0.1 the exposure is 100 times the 350 virions threshold for infection.
Staying together with the emitting person for 8 hours, the more so for two days, always reaches an exposure of well over 350 virions. At VR0.1 the two-day exposure reaches 470-thousand virions, nearly 1200 times the threshold of 350. This exposure corresponds to an alveolar infection of around 18-thousand virions, starting well into Day 11 in the alveolar infection model in SI-W1. Newly infected persons contribute to the room concentration, here left out of account.

Table 1. Potential exposures depending on time of stay of the infected person at entering of not-infected person (t) and the duration of stay (period) following

[t,period]	VR0.1	VR0.5	VR1	VR2	VR5	VR10	VR20	VR40	VR60
[0,1]	0	0	0	0	0	0	0	0	0
[60,1]	34	28	23	16	8	4	2	1	1
[240,1]	82	51	33	19	8	4	2	1	1
[480,1]	104	58	37	21	9	5	2	1	1
[600,1]	111	60	38	22	10	5	3	1	1
[1320,1]	151	81	52	30	13	7	3	2	1
[2760,1]	273	148	94	54	24	12	6	3	2
[0,5]	8	8	8	8	7	7	5	4	3
[60,5]	174	145	117	81	39	20	10	5	3
[240,5]	411	253	165	96	42	22	11	6	4
[480,5]	521	288	183	106	47	24	12	6	4
[600,5]	555	303	192	111	49	25	13	7	4
[1320,5]	753	408	259	150	66	34	17	9	6
[2760,5]	1365	738	469	271	120	62	32	16	11
[0,15]	75	72	69	64	52	38	24	14	10
[60,15]	554	455	363	249	118	61	31	16	11
[240,15]	1243	763	497	288	127	66	34	17	11
[480,15]	1567	866	550	318	141	73	37	19	13
[600,15]	1669	910	578	334	148	76	39	20	13
[1320,15]	2265	1225	778	450	199	103	52	26	18
[2760,15]	4103	2219	1410	815	360	186	95	48	32
[0,120]	3812	3079	2445	1695	857	465	243	124	83
[60,120]	6577	4784	3460	2146	966	500	255	129	86
[240,120]	10698	6323	4070	2357	1041	539	274	138	93
[480,120]	12899	7080	4500	2603	1149	595	303	153	102
[600,120]	13679	7442	4729	2735	1207	625	318	161	107
[1320,120]	18517	10017	6364	3681	1625	842	428	216	145
[2760,120]	33543	18145	11529	6667	2943	1524	776	392	262
[0,240]	12263	8681	6240	3935	1847	978	504	256	171
[0,960]	91126	52286	34012	19998	8939	4651	2374	1199	802
[0,1440]	159990	89542	57684	33688	14982	7781	3967	2003	1340
[0,2880]	471052	257805	164597	95515	42278	21917	11164	5635	3768

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Color explanation

	Hardly infectious exposures ('< 350' virions)
	For 5 minutes stay, infectious dose only with very low VRs
	For 15 minutes stay, serious chance of infection except for VR10 and higher
	For 120 minutes stay, serious chance of infection except for VR20 and higher
	Long stay, high chance of severe infection, up to >1000 times medium infective dose

Consider a larger number of Standard emitters per 100m^3 than five, present with a longer emitting time, and longer stay-together period than two hours, with many to-be-infected persons. This will lead to many persons exposed to a very high dose: a superspreading event. Empirical analysis with only partial analytics is in [58], and similar for SARS-1 in [59, 60].

4.5. Closed spaces airborne exhale concentrations & exposures (distance & duration dependent)

Exhales are relatively warm and humid, hence have buoyancy, and they have kinetic energy when leaving the nose and mouth unobstructed. Kinetics are reduced very fast when the exhale expands (try and blow out a candle with your nose). The nose/mouse exhale cone, upward curved, is variously estimated with a ~40 degrees opening [61-63]. Mouth exhales diffuse faster while nose exhales start more downward. At 45cm distance the speed drops below 25cm/s [62], in still air. Modelling can be approached most simply by a sphere expanding in the cone (as used for still air inside) but better by a wisp, as the duration of a typical exhale is 1.8 seconds. Single exhales (0.5L) of the Standard Person contain around 100 virions. The first part of the exhale then has reached the low-speed-high-dilution front while the last breath part still enters the cone, see Figure 4a and 4b in [62], copied in Figure A in SI-T5. Air disturbances determine further dilution, while the diluted warm and humid virion cloud will still rise somewhat. After diluting to 50cm distance the one-sphere model gives a volume of 200L, a dilution by a factor 400, with 0.25 virions per 1/2L inhale there. This first approach is a substantial overestimate. The wisp model is more realistic. Being in the exhale for a longer period (100 inhales, 6 minutes and longer) would better be approached with the room model.

The burst exhale by cough-sneeze is approached with the lab situation in [64], assuming 5 times the normal exhale virion load. The dilution at 1m shows a radius of 50cm, and from there dilutes further, following a narrow cone at around 10 degrees at least. Five times inhale in the full cough, highly unusual, leads to an exposure of 7.5 virions at 100cm, and 6 and 5 virion at 150 and 200cm. The 40-degrees cone model would similarly lead to 6.2, 1.8 and 0.75 virions respectively. See the basic spreadsheet results, open to making variants, in SI-W19.

4.6. Open spaces airborne concentrations and exposures (location and duration dependent)

Empirical models to quantify the concentrations and exposures are fully lacking at scale level up to 20 meters. Fluid dynamics might model the transport and dilution of exhales but cannot be reduced to generic situations and mechanisms. A first step for quantification is to define an exemplary situation for modelling. We consider a 10x10m square with one person per 1m^2, all at 1m distance. Persons are at most 13m apart, on a diagonal. The gathering lasts 4 hours. Five Standard Persons are assumed to emit in the 100 persons crowd, an infectious density of 5%. [65] At US-state level the density was measured at 1.7% 65], but in groups it can be higher. Two emitting persons stand directly in line, with a very modest wind of 1m/s (at the boundary between Beaufort 0 and 1, Calm to Light Air). Exhales of a typical person last half of their tidal flow of 3.6 seconds, 1000 flows of 0.5L per hour, 0.5m^3. Each Standard Person exhales 100 virions per exhale of 1.8 seconds, 100,000 per hour. Two persons exhaling in tandem could create a continuous flow wisp, one after the other. Shifting the tandem in time would not alter the average concentrations.

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At exhalation, kinetics, moisture, and temperature drive dilution, up to half a meter, as was shown in inside still air models. The exhale cone opening is estimated at ~40 degrees. The wind, set at a low 1m/s, creates transport and turbulence. Empirical data in a 200m range (SI-T6 and SI-W20) from [49] suggest that the concentration reduction by distance from the source is independent of wind speed, with a cone opening of ~10 degrees. It is superimposed on the 40 degrees cone with a combined cone of 45 degrees, up to 70cm, and 10 degrees thereafter. See SI-T5 for modelling options.

The exposed person is in the same line of wind, at different distances, inhaling 0.5L per tidal flow.

Simplifying assumptions were added for modelling, depicting worst-case situations. Vertical rising and mixing, at micro, meso, and macro level, major factors in ground-level dilution [47], were left out of account. We checked for the effect of other simplifying assumptions. Modelling perpendicular dispersion continuously only does not influence average concentrations. Lifting the assumption of synchronous in-tandem exhalation of the two emitters does not either. We compared the outcomes with a rough expanding sphere model and with a virtual room model. They depict exposures in a similar domain, with even at only 1m a near zero risk of infection.

Table 2. Exposures at different distances on 100m2 terrace, two emitting persons in line.

Exhaler 2 stands 100cm downwind from Exhaler 1. Windspeed 1m/s. Exposure period 4 hours.

Inhaler from Exhaler 1 in cm	*175*	*200*	*500*	*1000*	*1500*
Virions inhaled from Exhaler 1	48	44	20	8	5
Virions inhaled from Exhaler 2	70	63	25	10	5
Total Exposure Person X	**118**	**108**	**45**	**18**	**10**

The highest exposure is with the inhaler mid-head at 75cm from exhaler 2, 118 virions. Face-to-face that corresponds to an unusually close ~50cm distance, 4 hours long. Reckoning with 2 hours would halve the exposure. Other persons on the terrace will have a lower exposure than those standing in the two exhalers-in-row-in-line-with-wind exhales.

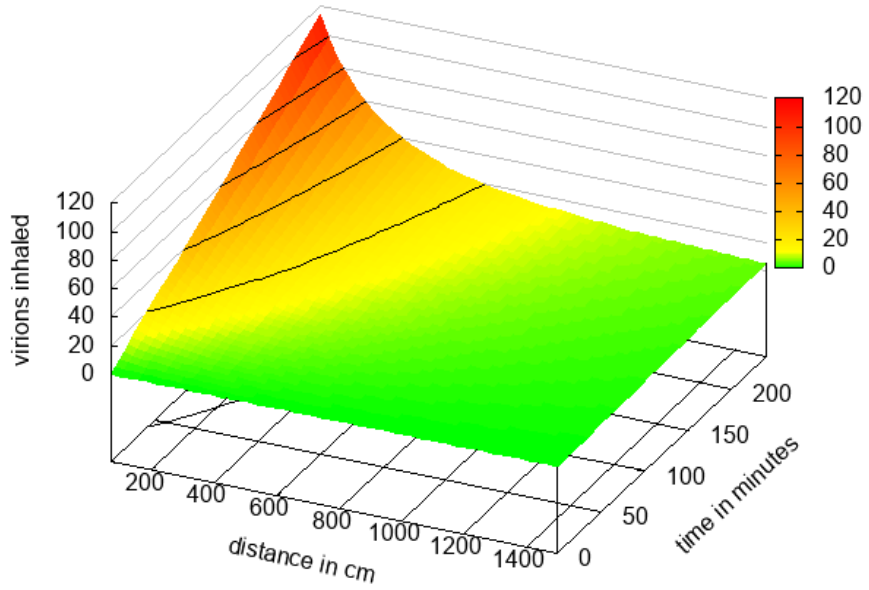

Figure 4. Exposures on a terrace depending on distance and duration

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Two emitting persons in line, inhaler distance from the first, 4 hours. Iso-exposure lines in black.

4.7. Direct and indirect fluid and solid exposures

Several modelling steps are required for direct exposure and infection, by fluids or solids. Virus containing exhaled droplets and stool first are to reach the nose or mouth. When arriving there they are not airborne, so a next model step is required for transport to the ACE2 cells in the back of the mouth and ceiling of the nose, with next the production of airborne viruses there, which then may reach the alveoli. These would have to be inhaled in relevant quantities for alveolar infection.

The indirect environmental route adds various steps to be modelled. First, droplets fall on objects, spreading out and drying up. Next, fingers and hands must take up the virions, a limited share at most. Then the virions are brought to the mucus rich nose and mouth, again a share at most. The exposure is at least an order of magnitude smaller than the low-chance direct droplet hit. The steps to infection are the same as for direct exposure. Stool might contain viable virions, see SI-W18, which may be brought to nose and mouth by hand. High estimates of virion content and effective routes to exposure still show very low exposures. The extensive treatment of these exposure routes is in SI-T9.

Overall, the direct and indirect routes to SARS-2 exposure and infection seem very minor as compared to airborne exposures in many normal situations.

4.8. Other sources of exposure

The ultimate source is in bats, with species in Northern Laos carrying SARS virions most similar to SARS-CoV-2 [66]. Animal-to-human infection has been documented in the vicinity of mink farms [67], with mink farms in Northern Jutland constituting a main source of human infections there, see the broad survey in [68], also covering ferrets. Ferrets, widely held as pets, can be infected with SARS-2, experiencing alveolar and broader infection [68, 69]. At around 1.5kg, ferrets constitute 0.02 standard-person-equivalent. At VR1 in a 20m^3 bedroom, a one-night intake may reach 680 virions, with 1823 virions at not uncommon VR0.1. Quantified measurements to support this route are lacking, however.

Next to minks and ferrets, there is a broad range of pets, captive and wild animals carrying the SARS-2 virus [69, 70]. Quantified risks from their exhales, as from using them as pets or treating and using them for food, seem lacking and are assumed by these authors to be low.

Frozen food and its packaging may remain contaminated for a long time, as found several times in China, with a chance of infection especially by the mouth-to-intestines route. The source then is human or animal emissions elsewhere.

5. Modelling from exposure to infection

5.1. Available partial models and data, and gaps

The SARS-2 pneumonia infection requires the full route through nose, mouth, and further airways, the virions next passing the ~25,000,000 finest bronchioles to the ~500,000,000 alveoli, see [43], p.477). There is substantial knowledge on the physical filtering capacity of the airways, and on the transport of caught particles to the throat, mostly followed by swallowing. But quantified modelling is lacking. The epithelial cells also de-activate virions, so PCR measurements cannot give a reliable indication on the number of viable virions coming up after inhalation or after infection. Most virions in mucus will be swallowed. As there is a near full coinfection of the small intestines with alveolar infection, the swallowing route seems probable. The route through blood to the intestines might be possible as well, as the blood connected surface there is high, in the order of 30m^2. The many smaller spots in the body with ACE2 cells may get infected as well, ranging from heart muscles to small arteries and salivary and sweat glands, with possible in-body infection routes. Human challenge trials with quantified droplet infection in the nose [71] might shed some light on this issue, if the intestine infection route would be part of the research. It was not. Results of standardized droplet infection

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in the nose are interesting however, see [72], under review. Thirty-four not previously infected persons, under forty years of age, were inoculated with droplets in the nose, using the original SARS-2 variant. Eighteen became positive, measured with PCR-tests on nose and throat swabs. None of them developed COVID-19 pneumonia from their nose-throat infection.

Tidal flows to the alveoli are explained in [73], p.16509, and in [74], see also our Figure 2. Larger droplets, close-by still floating in the air, 5-10μm, may be deposited in nose/mouth and high upper airways, see SI-W17 for size relations and virion content. Medium size particles, 1-5μm, are taken out by mass inertia in the upper airways as well. Small particles below 1μm, smallest more effectively, may reach the alveoli. (Conversely, larger particles if they were produced there, can hardly leave the alveoli.) Airborne inhales below 1μm will partly reach the alveoli; will partly be caught in mucus; and will partly move upwards again at exhalation. That tidal flow will partly leave the exposed person and will partly go down again towards other alveoli, in the next tidal inhale. The filtering efficiency of the airways can differ strongly between persons. Lung-compromised persons receive a substantially higher amount of UFPs in their alveoli than healthy persons [75] and see the survey on UFPs and health in [76]. Similarly, medicine application in the lungs are UFP-size and smaller for most effective up to alveolar application [32] and see in more detail [34].

The models and figures for influenza exposure and infection would substantially differ from those of SARS-2. Even the later Omicron variant may behave different from the previous variants. It shows lower infectiousness in the alveoli and alveolar sacs than previous variants according to [77], leading to a cold-like illness mostly. The flu virus is basically different as it does not replicate in the alveoli but in nose, throat, and airways, and may then accommodate a bacterial pneumonia in the alveoli indirectly, as with pneumococcus variants. Neither does influenza replicate in the intestines' cell linings but causes injury and illness there only indirectly [78]. The influenza virus starts replicating where droplets get caught in throat-mouth-nose and the upper airways. Airborne infection with droplets may therefor play a main role for influenza [79], and see an early case study [80], with ¾ of all persons in a room infected within 3 hours. The age distribution of infected and ill persons in an epidemic differs extremely between SARS-2 and influenza, with influenza dominating in younger persons as older persons will have developed defenses in earlier epidemics already, see [81].

The conclusion here is that the relation between oral-nasal exposure and alveolar infection has not been established for droplets. Single virions and small, possibly viable virions containing clusters, can reach the alveoli directly, in infectious amounts. The required minimum dose for alveolar infection is not well known. For illustrative reasons we roughly follow [44] with 350 as middle value, and use 100 virions as a lower boundary for a relevant chance of infection, and >1000 virions as high chance.

5.2. Droplet and solid infection through nose and mouth

In the upper nose cavity, ACE2 cells are present in the supportive lining of the olfactory nerves, with fast ACE2 cell replication after infection. Small amounts of ACE2 cells are in the saliva-rich back of the mouth and in the throat, and in conjunctival parts of the eyes. For COVID-19 pneumonia, the eye infection will have to advance through the nose. The nose may be infected at airborne inhalation; by a droplet hit towards the upper nose cavity; or indirectly by infected finger contact, all requiring an in-nose model for deeper infection. There is no quantified modelling of these routes to pneumonia; how the virions produced in nose, mouth, and throat can access the alveoli.

The only-nose infection might start an early SARS-2-specific defense, possibly leading to a less serious later illness [82] and see also related to loss of smell [83, 84]. Results of [72] are in line with these observations.

Overall, the airborne infection route with single virions or small virion containing particles is required for COVID-19 pneumonia. Airborne exposure seems the core route for this illness, dominated by the smallest virion forms.

6. Results for quantified exposure scenarios

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6.1. Descriptions of situations linked to modelling outcomes, with scenarios.

Real life situations are linked to modelling outcomes, with a broad range of relevant scenario combinations selected. The concentration development in closed space situations is scalable to volume and number of emitters. One emitting person in 20m^3 (~8m^2) gives the same concentration build-up as 5 emitters in 100m^3 (~30m^2), larger rooms. The start of an inhaling stay is specified per situation, as is the duration. If the standard person of 100 000 virions per hour is replaced by an exhaler of 10,000, all figures divide by 10. The range from VR0.1 to VR60 covers most practical situations. Concentrations do not relate linearly to VR changes. The basic data for Table 3 are in Table 1 in SI-W14, with extensive sensitivity analysis there.

Inhaling persons are at least 75cm apart from exhalers. Regular exhale exposures are 100 times. A cough-sneeze burst directly in the face is a one-time event only.

Outside situations refer to 100m^2 square with 1 person per m^2 and five persons infectious. Duration of stay is four hours. Exposures are linearly scalable in time. Concentration build-up and virion breakdown remain negligeable. The location of emitters and exposed persons determines potential exposure, see Figure 4. Wind displacement is taken very low at 1m/s superimposed on the exhale dilution, while disregarding other causes of turbulence and dilution, especially as related to vertical transport.

6.2. Exposures in selected situations and scenarios, quantified.

Table 3 gives the outcomes in terms of potential virion exposures. Colors indicate severeness of potential exposures. Dark green is the not yet infectious dose of below 100 SARS-2 virions and light green a low chance of infection, still below 350 virions. Light red is some real chance of infection, between 350 and 1000 virions and red, above 1000 virions, indicates a substantial chance of infection.

Short exposures (15 minutes) in closed spaces with a standard density of 5 emitting persons in 100m^3 poses a negligible risk, even at low VRs. Very high VRs preclude a serious exposure except with a high density of emitting persons and a long period of stay.

With longer durations in a room where emissions lead to a high concentration, exposures rise dramatically. Even in a reasonably ventilated room (VR5) where one ill person (per 20m^3) had been for 1 hour already, the exposure for the person remaining there for another 2 hours comes at 966 virions: high infection risk. With larger numbers of emitting persons, as in sick rooms in care situations with moderate ventilation, infectious exposure is near inevitable.

Incidental cough-sneeze right in the face lead to exposures well below 100 virions, even with some repetition.

In outside gatherings with 5 emitting persons per 100m^2 and hardly any wind, an infectious exposure seems near impossible.

A large set of situations with scenarios is in SW-W21, ordered as to potential exposure in SI-W22. A qualitative evaluation of all treated situations reckoning with key scenarios is in SI-T8.

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Table 3. Exposures in selected situations and scenarios

The table is in spreadsheet SI-W23. The precision of numbers is much lower than indicated.

Situations:	Exposure scenarios:							
	ill ratio	Maximum density (or distance)	Emitting persons	Start time, period	VRs/ Liter	Exposure to virions	Relative to Ref. 350 virions	Ref. Super-market 15 min.
Bedroom, private, low VR	50%	2/8m2;h2.5m	1/20m³	t0,960	0.1	**91126**	**260**	**11506**
Patient ward, sleeping, low VR	50%	10/30m2;h3.3m	5/100m³	t0,960	0.1	**91126**	**260**	**11506**
Train compartment long distance	33%	6/8m2;h2.5m	2/20m³	t0,960	2	**39996**	**114**	**5050**
Bus long distance	5%	60/80m2h;2.5m	3/100m³	t0,960	2	**11999**	**34**	**1515**
Office room	25%	5/30m2;h3.3m	2.5/100m³	t0,960	2	**9999**	**29**	**1263**
Bar	16.7%	30/30m2;h3.3m	5/100m³	t240,120	1	**4070**	**12**	**514**
Coffee room (choir, clubs)	6.7%	30/30m2;h3.3m	5/100m³	t60,120	1	**3460**	**10**	**437**
Pets, ferrets in sleeping room		2/20m³	0.02/20m³	t0, 960	0.1	**1823**	**5**	**230**
Minks farm, person-equivalent	50%	20/25m2; 4m	10/100m³	t2760,120	20	**1552**	**4**	**194**
Restaurant inside full	6.7%	30/30m2;h3.3m	2/100m³	t60/120	1	**1384**	**4**	**175**
Long Term care dining room	50%	10/30m2;h3.3m	5/100m³	t60,120	5	**966**	**3**	**122**
Patient ward visitor morning	10%	10/30m2;h3.3m	1/100m³	t600,120	1	**946**	**3**	**119**
Bus, metro commuting, busy, long	12.5%	40/40m2;2.5m	5/100m³	t0,120	5	**857**	**2**	**108**
Sitting room	20%	5/30m2;h3.3m	1/100m³	t240,120	1	**814**	**2**	**103**
Person car ventilation low, not off	50%	4/10m³	2/10m³	t0,240	20	**806**	**2**	**102**
Airplane, long distance (SI-W1)	10%	10/3m2;2.2m	1/20m³	t0,960	60	**802**	**2**	**101**
Dining room, guests, full	20%	15/30m2;h3.3m	3/100m³	t0,120	5	**514**	**1**	**65**
Church	2%	50/200m2;10m	1/100m³	t0,240	1	**374**	**1**	**47**
Train compartment	3.3%	6/8m2;h2.5m	0.2/20m³	t0,240	5	**369**	**1**	**47**
Airplane, short distance (SI-W1)	10%	10/3m2;2.2m	1/20m³	t0,120	20	**243**	**0.69**	**31**
Office room	2.5%	5/30m2;h3.3m	2.5/100m³	t0,960	10	**233**	**0.67**	**29**
Shop, ill ventilated	50%	5/30m2;h3.3m	2.5/100m³	t60/15	0.5	**228**	**0.65**	**29**
Bar	6.7%	30/30m2;h3.3m	2/100m³	t60/120	10	**200**	**0.57**	**25**
Dining room, small family	20%	5/30m2;h3.3m	1/100m³	t0,120	5	**171**	**0.49**	**22**
Sitting room	20%	5/30m2;h3.3m	1/100m³	t0,120	5	**171**	**0.49**	**22**
Coffee room (choir, clubs)	6.7%	30/30m2;h3.3m	5/100m³	t60/15	5	**118**	**0.34**	**15**
Terrace outside, exhales & wind		2 exhalers, row	175cm aft. nr1	240 min.	1000L	**118**	**0.34**	**15**
Terrace outside, exhales & wind		2 exhalers, row	2m after nr1	240 min.	1000L	**108**	**0.31**	**14**
Restaurant inside full	3.3%	30/30m2;h3.3m	1/100m³	t60,120	10	**100**	**0.29**	**13**
Shopping mall,	4%	5/30m2;h3.3m	0.2/100m³	t60/120	2	**86**	**0.25**	**11**
Dressing room (sport, etc.)	33%	15/30m2;h3.3m	5/100m³	t0,15	1	**52**	**0.15**	**7**
Church (high building)	2%	50/200m2;10m	1/100m³	t0,120	5	**51**	**0.15**	**6**
Meeting room	2.5%	10/30m2;h3.3m	2.5/100m³	t0,120	5	**43**	**0.12**	**5**
Bus, metro commuting, few	5%	40/40m2;2.5m	2/100m³	t60,15	2	**40**	**0.11**	**5**
Terrace outside "room model"	HL30	100/100m2	5/500m³	t0,240	60	**33**	**0.094**	**4**
Exhales normal face-to-face	better use room model		100cm	100x, 6 min.		**25**	**0.071**	**3**

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Person car ventilation medium	50%	4/10m^3	2/10m^3	t0,15	40	**22**	**0.064**	**3**
Health club, groups	8%	25/250m2;h4m	2/1000m^3	t0,120	10	**19**	**0.053**	**2**
Terrace outside, exhales & wind		2 exhal. in row	10m after nr1	240 min.	1000L	**18**	**0.051**	**2**
Supermarket, well-ventilated	6%	10/30m2;h3.3m	2.5/100m^3	t60/15	10	**8**	**0.023**	**1**
Train compartment	3.3%	6/8m2;h2.5m	0.2/20m^3	t0,15	20	**5**	**0.014**	**0.63**
Exhale cough-sneeze full inhale	burst + 10 degr. cone		100cm	5x		**1.47**	**0.0042**	**0.19**
Platform railway/bus, exhales		50/100m2	75cm distance	6 min.	25L	**0.18**	**0.0005**	**0.023**

Legenda

below low infectious dose (< 100)	high infectious dose (350 - 1000)
low infectious dose (100 - 350)	extreme infectious dose (> 1000)

The table is in spreadsheet form in SI-W23.

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7. Conclusions

7.1. Results for environmental science

- The domain of short-lived toxic substances, see [8], can be expanded to include short-lived toxic biotic substances, such as virions, and possibly protists and biotic toxins like prions, see exemplary [85]. SARS-CoV-2 will not be the last pandemic to reckon with.
- The factory-to-exposure structure will differ in its details per virus type, as is the case with other short-lived toxic substances. Their decay and transformation characteristics must be developed. Some more case studies, including for influenza, would be useful, with improved measurements and modelling steps. The header could be *Viral Substance Flow Analysis*, or broader: *Biotic Substance Flow Analysis (BSFA)*.
- Environmental science could fill the gap in knowledge which now leaves the relative and absolute importance of preventive measures unsubstantiated.

7.2. Results for medical sciences and epidemiology

- The daily development model of alveolar infection and emissions (SI-W1) gives a framework for assessing the effect of light versus severe exposures. High exposures lead to high emitters, and probably to more such emitters for a next round of high exposures. Super-spreaders and super-spreading events could be explained this way.
- Given the duration between infectious exposure and the build-up of specific defenses, the illness model can also help explain the difference in the rate and seriousness of infection of similar groups and regions at different times.
- Swallowing virions through esophagus and stomach seems a viable option for small intestines infection. Infection routes between the small intestines and the alveoli may be blood based, bidirectionally, also involving other ACE2 containing tissues.
- Improved and standardized measurement of viable virions is highly urgent, covering different persons at different illness stages, with concentrations and exposures to be measured in a broad range of situations.

7.3. Results for citizens and governments

Exposures and infections

- Potential exposure situations differ by well over four orders of magnitude. The highest exposures will have a substantial chance of infection, while the lowest seem irrelevant.
- In open air and in well ventilated places, and through contact with droplets and fomites, there is a near zero exposure and hence negligible chance of COVID-19 pneumonia.
- One cough full in the face at one-meter distance delivers on average less than 1 single virion into the nose, let alone deep into the lungs to the alveoli. Having dinner with that person in its reasonably ventilated (VR5) 7m^2 kitchen, gives a one thousand times higher exposure, at any sitting distance. The inhalation there involves airborne virions reaching the alveoli.
- Very high exposures result virtually only in low-ventilated spaces, with larger numbers of emitting persons per cubic meter, and a long duration of stay.
- The focus on singing and speaking cannot be justified. Larger droplets, and more of them, may be exhaled, but the primary production in the alveoli is not influenced. The number of virions produced will be diluted over more exhale volume and more fluid, of a size not reaching the alveoli.
- The number of free virions exhaled per unit of time may hardly be influenced by the speed of exhaling.

Measures

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- Preventive measures can focus on reducing high-exposure situations. Short-term, many such situations can be avoided or can be reduced substantially by increased ventilation.
- High but perfectly feasible ventilation rates can reduce exposures to virtually zero. This is also possible in well-designed collective transport, often available now already.
- Long duration transport may require higher ventilation rates than VR17, now assumed enough for airplanes, or would require well-designed flow ventilation.
- Adequate ventilation and equivalent air filtering systems are present in many situations with public access already, and may be further introduced, then standardized and controlled.
- Medical masks, assumed two-thirds effective, would reduce intake to one third. In high concentration situations, exposures would still be high, the more so with nonmedical masks.
- Masks, any, seem irrelevant outside, and inside as well in well-ventilated situations, as concentrations are too low for infection already.
- Social distancing is fully ineffective in well-mixed contaminated spaces, where concentrations are equal on all spots. It is also irrelevant outside and in well-ventilated hence not-contaminated spaces.
- Handwashing and surface cleaning do not reduce COVID-19 risks as these infection routes are not relevant for SARS-CoV-2, in contrast possibly to the flu and some bacterial infections.

Policy strategies

- The responsibility to create a non-infectious surrounding might be placed with those managing publicly accessible spaces, aided by public certifications and checks on maintaining effective ventilation. This includes workplaces and offices, shops and supermarkets, the catering industry and clubs, and situations of longer stay such as care situations.
- Ill-ventilated private homes can be approached with technical and behavioral advice now and long term through building regulations for existing and new buildings, as present in several countries already.
- At future high infection rates, focused public policy measures may control the fewer high-exposure spaces remaining.

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