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Higher viral load and infectivity increase risk of aerosol transmission for Delta and Omicron variants of SARS-CoV-2

Michael Riediker[a]*, Leonardo Briceno-Ayala[b], Gaku Ichihara[c], Daniele Albani[d], Deyan Poffet[e], Dai-Hua Tsai[a], Samuel Iff[f], Christian Monn[f]

[a] Swiss Centre for Occupational and Environmental Health, Winterthur, Switzerland
[b] Universidad del Rosario, Escuela de Medicina y Ciencias de la Salud, Bogota, Colombia
[c] Tokyo University of Science, Faculty of Pharmaceutical Sciences, Health Management Center, Chiba, Japan
[d] Repubblica e Cantone Ticino, Dipartimento del territorio, Camorino, Switzerland
[e] Centre for Primary Care and Public Health (Unisanté), Department of Occupational and Environmental Health, Lausanne, Switzerland
[f] State Secretariat for Economic Affairs (SECO), Working Conditions Section, Bern, Switzerland

Summary

BACKGROUND: Airborne transmission of SARS-CoV-2 is an important route of infection. For the wildtype (WT) only a small proportion of those infected emitted large quantities of the virus. The currently prevalent variants of concern, Delta (B1.617.2) and Omicron (B.1.1.529), are characterized by higher viral loads and a lower minimal infective dose compared to the WT. We aimed to describe the resulting distribution of airborne viral emissions and to reassess the risk estimates for public settings given the higher viral load and infectivity.

METHOD: We reran the Monte Carlo modelling to estimate viral emissions in the fine aerosol size range using available viral load data. We also updated our tool to simulate indoor airborne transmission of SARS-CoV-2 by including a CO_2 calculator and recirculating air cleaning devices. We also assessed the consequences of the lower critical dose on the infection risk in public settings with different protection strategies.

RESULTS: Our modelling suggests that a much larger proportion of individuals infected with the new variants are high, very high or super-emitters of airborne viruses: for the WT, one in 1,000 infected was a super-emitter; for Delta one in 30; and for Omicron one in 20 or one in 10, depending on the viral load estimate used. Testing of the effectiveness of protective strategies in view of the lower critical dose suggests that surgical masks are no longer sufficient in most public settings, while correctly fitted FFP2 respirators still provide sufficient protection, except in high aerosol producing situations such as singing or shouting.

DISCUSSION: From an aerosol transmission perspective, the shift towards a larger proportion of very high emitting individuals, together with the strongly reduced critical dose, seem to be two important drivers of the aerosol risk, and are likely contributing to the observed rapid spread of the Delta and Omicron variants of concern. Reducing contacts, always wearing well-fitted FFP2 respirators when indoors, using ventilation and other methods to reduce airborne virus concentrations, and avoiding situations with loud voices seem critical to limiting these latest waves of the COVID-19 pandemic.

Correspondence:
Michael Riediker, Dr.sc.nat. ETH
Schweizerisches Zentrum für Arbeits- und Umweltgesundheit (Swiss Centre for Occupational and Environmental Health)
Binzhofstrasse 87
CH-8404 Winterthur
michael.riediker[at]alumni.ethz.ch

Introduction

What is the virus concentration in a room when infected humans exhale aerosols and what is the resulting dose and associated risk for other humans in that room? We previously described an approach to modelling these questions [1]. It combines the viral load in the lungs and throat with the known emissions of respiratory aerosols. The resulting viral emission strength can be used in a well-mixed room simulation that also considers the room size, the air exchange rate and the half-life of the virus when airborne. Our modelling suggested that critical virus concentrations can be reached rapidly if an infected person has a high viral load, particularly in poorly ventilated rooms. Building on this concept, we subsequently developed a Monte Carlo model that described the expected distribution of viral emissions for a population of infected people that are either silent, speaking softly or speaking loudly [2]. We published with it a spreadsheet-based tool, an indoor scenario simulator that provides a rapid assessment of the indoor airborne transmission of SARS-CoV-2 as a function of room and ventilation parameters, different vocal and physical activities and the types of masks worn by the emitter and the receiver. This tool includes estimates for the "near-field", the zone in close proximity to the emitter. We updated the tool by adding a recirculating air purification parameter and a CO_2 simulator.

These initial models were developed for the wildtype (WT) of the virus. In the meantime, several new variants of concern have emerged. In particular, Delta (B1.617.2), and even more so Omicron (B.1.1.529), are reported to be very transmissible and to spread rapidly [3, 4]. Currently available data suggest that all variants of concern have a higher viral load than the WT [3, 5–8]. In the United Kingdom, the average polymerase chain reaction (PCR) cycle threshold (CT value) for samples with S-gene target failure dropped rapidly from around 30 before Omicron to 23 at a time when Omicron still only accounted for a single digit percentage of the infected population [3]. Extrapolating this curve suggests that the average viral load of Omicron is about ten- to one hundred-fold larger than that of Delta.

Delta and Omicron both also have increased transmissibility: the number of cells infected for a given number of ribonucleic acid (RNA) virus copies was found to be doubled and quadrupled respectively [4]. Furthermore, Omicron also seems to be better at evading the immune system. This implies that the critical dose of virus copies above which a situation is potentially infectious needs to be lowered. For the WT, we had proposed a critical dose of 500 virus copies [2]. If the above-mentioned capacity to infect cells translates into an infection risk, this would imply a critical dose of around 300 virus copies for Delta and around 100 virus copies for Omicron.

Here, we aim to estimate the risk resulting from the higher viral load and infectivity observed for the new variants of concern. For this, we estimated the frequencies of high, very high and super-emitting individuals in the population and assessed the consequences of a lower critical dose.

Methods

We modelled the emission distribution of the infected population using the previously described Monte Carlo approach [2]. Briefly, we took random samples from the documented population distribution of aerosol emissions for different vocal intensities to calculate the volume released in the fine particulate matter size range. We then multiplied this aerosol emission volume with a random sample from the viral load to obtain the viral emission in the form of fine aerosols. We repeated this random sampling approach 100,000 times to obtain the combined distribution in the population.

To model the variants of concern, we changed the source of the viral load distribution as follows: for Delta, we assessed published data [6–8] and took, in each Monte Carlo iteration, a sample from a log-normal distribution with a mean of $10^{8.5}$ virus copies ml^{-1}. For Omicron, we randomly sampled from two hypothetical log-normal distributions. In scenario "Ox10" ("Omicron has ten times the viral load of Delta"), we used a mean of $10^{9.5}$ virus copies ml^{-1}, while in scenario "Ox100" ("Omicron has 100-fold more viral load than Delta") we used a mean of $10^{10.5}$ virus copies ml^{-1}. In all three models, we assumed an interquartile range of 10^3, corresponding to a log-10 standard deviation of 2.2239, and resampled viral loads above 10^{12} virus copies ml^{-1} in order to not greatly exceed the highest ever reported viral load [9].

The tool for simulating the viral concentration in the indoor air and the resulting viral dose was described earlier. It is based on a near-field/far-field well-mixed model [1, 2] that uses as its source-estimate the emission rates for viruses in aerosols when a person is silent, talking softly or talking loudly. The user can adjust viral emissions factors such as vocal loudness, degree of physical activity and mask types worn by the emitter; room characteristics such as room volume, air exchange rate and average air velocity; and recipient-side factors such as mask wearing and critical viral dose. The near-field/far-field well-mixed model [10] then combines these factors with the half-life of the virus in the air and provides the viral dose after a given time in the room and the time until the critical dose is reached [11]. The near-field portion of the model simulates the air in the space immediately surrounding the emitter, while the far field portion describes the rest of the room.

In the recently updated version, we replaced the single air exchange term with two terms: outdoor air supply and recirculating air cleaning devices, both expressed in air exchange rate equivalents. For the recirculated air exchange, we further specified that the hourly clean air delivery rate (CADR) divided by the room volume is to be entered. The tool combines the two rates into one joint rate when calculating the virus concentrations. We also added a CO_2 calculator to the tool, which estimates the CO_2 concentration in quarter-hourly intervals, as well as when leaving the room. The CO_2 calculator also uses a well-mixed room equation but takes into account the outside air supply only. It assumes an exhaled CO_2 concentration of 35,000 ppm and sets the respiratory volume according to the exercise level of the emitter. By default the tool assumes a starting concentration of 400 ppm, but it allows experts to define other starting values. We also took into account that many people wear masks that are not well fitted to their face by adding a category “ill-fitting mask”, defined as a “community or hygiene mask that does not fit snugly to the nose, cheeks or chin, leaving gaps there”. Its efficiency was set to 40% in both respiratory directions. Graphs for the time course of viral dose and of CO_2 concentration in the first two hours complement these changes. They contain references to the user-defined critical viral dose (set by default to 300 virus copies [2]) and to general indoor air quality guidance for CO_2 concentrations [12–14] of 800 to 1,000 ppm (start of reduced cognitive performance and sick building syndrome), 2,000 ppm (start of physical health effects such as fatigue, headaches, etc.) and 5,000 ppm (eight-hour occupational limit value in Switzerland and other countries). The tool was translated into many different languages and is made freely available from the first author's institutional website (https://scoeh.ch/) under a Commons Attribution license.

Results and discussion

Figure 1 shows the distributions of viral emissions by the infected populations when speaking quietly for the different variants. The distributions for breathing only and speaking loudly (not shown) look identical but are shifted to lower and higher values respectively. For Delta, and even more so for Omicron, the distribution is shifted towards very high viral emissions. In the new version of the tool, we maintain the emitter strengths used earlier [2] to define high, very high and super-emitters to ensure consistency between different versions of the tool. It is important, however, to recognize that these emitter types now represent a much larger proportion of the infected population. Most notable is the strong increase in the frequency of super-emitting individuals, represented in Figure 1 by the area under the curve to the right of the line marking the super-emitters.

Table 1 lists the emission strengths for speaking quietly and compares the key emission characteristics for the WT, Delta and the two Omicron estimates. Super-emitters used to represent about one in 1,000 infected with the WT. They have become much more frequent: amongst those infected with Delta it is one in 30; and for Omicron it is one in 20 or one in 10, depending on the viral load estimate used. Super-emitters' emissions can rapidly lead to concentrations in indoor environments that were previously associated with super-spreading events [2, 15–18]. This increase is therefore of great concern. But the increases in the proportion of high and very high emitting individuals should not be overlooked. Such emitters can, in a short time, cause critical concentrations in medium-sized and small rooms respectively. This implies that for Omicron, one half to two thirds of the infected population emit sufficient virus into the air to pose a realistic infection risk to others by airborne transmission. In conclusion, the increased viral load seems likely to be a key contributor to the observed rapid spread of the new variants of concern [3, 19].

A further challenge is the much higher infectivity [4], which means that a much lower dose is sufficient to transmit the virus. Table 2 lists frequent public situations that we simulated when the WT was prevalent [2]. Most situations in offices, restaurants, discos and on public transport could be sufficiently addressed by correctly wearing a surgical face mask. However, for Delta many of these situations have become critical (defined as being above the critical dose). For Omicron, almost all are now critical or even very critical (more than double the critical dose). In most situations, FFP2 respirators will still provide sufficient protection because they remove at least 95% of

Figure 1: Distribution of viral emissions in populations infected with the WT, the Delta and the Omicron variants when speaking at low vocal intensity. Red lines indicate the high emitter (90th percentile of WT), very high emitter (99th) and super-emitter (99.9th) thresholds. Ox10 and Ox100 indicate simulations for Omicron assuming 10 times and 100 times higher mean viral loads compared to Delta.

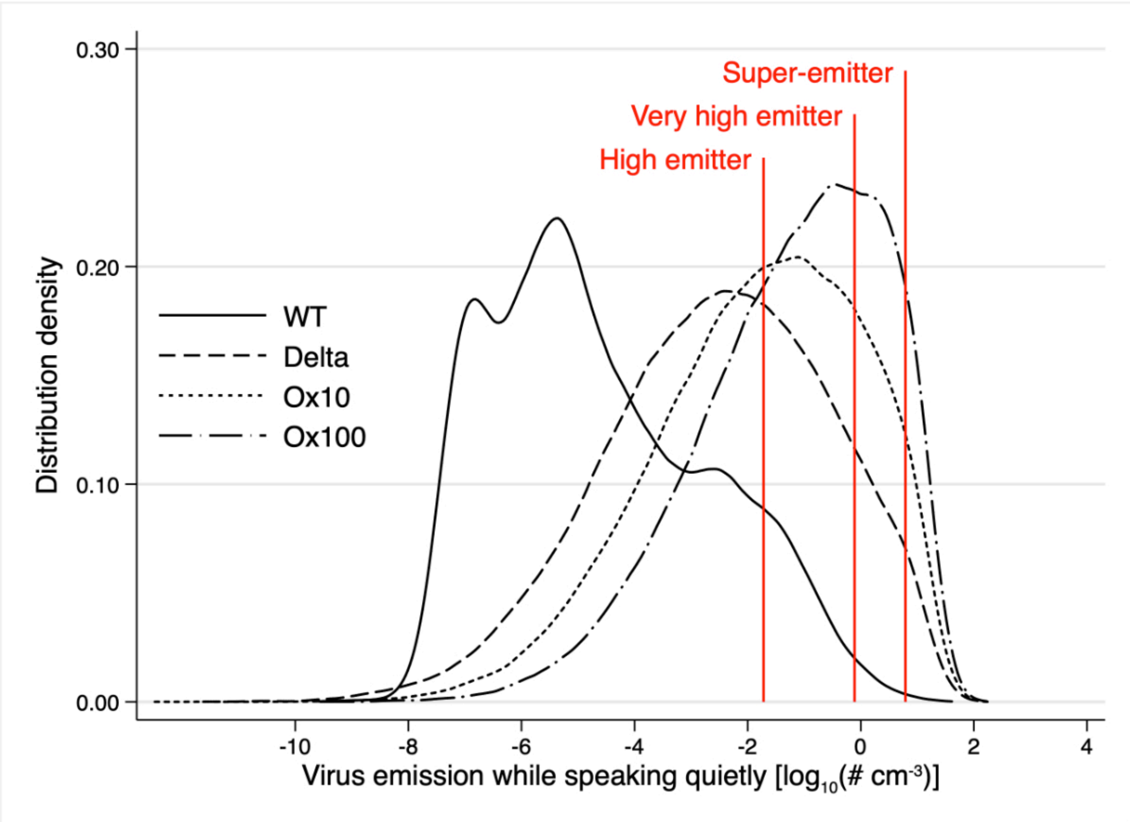

Table 1:
Descriptive statistics of viral emissions in the PM_{10}-sized fraction with quiet speaking for published viral load data for Delta and for two viral load estimates for Omicron (Ox10 and Ox100). For the predefined emitter types, the percentile (pct.) in the WT distribution and the new percentiles are shown.

Statistics for speaking quietly	Delta [copies cm $^{-3}$]	Ox10 [copies cm $^{-3}$]	Ox100 [copies cm $^{-3}$]
Mean	0.667	1.197	1.900
Standard deviation	2.97	4.01	5.22
1st percentile	2.55E-08	2.38E-07	1.89E-06
Median	0.00366	0.0225	0.0998
99th percentile	13.75	19.20	24.81
New percentiles of emitter types			
High emitter (WT = 90th pct.)	63rd pct.	48th pct.	35th pct.
Very high emitter (WT = 99th pct.)	88th pct.	80th pct.	70th pct.
Super-emitter (WT = 99.9th pct.)	97th pct.	94th pct.	90th pct.

Table 2:

Consequences of lower critical doses for frequent public situations in the presence of a super-emitter. Everybody is wearing surgical masks unless otherwise indicated (partly reproduced from [2] under CC BY 4.0). ACH: air changes per hour. Vocal intensity: “talk” = low intensity vocal activity. Interpretation: “critical" = above critical dose, “very critical” = more than twice critical dose.

Scenario	Dose in far field	Interpretation for virus variant		
	[copies received]	WT	Delta	Omicron
4 hours in small office (50 m^3, 1 ACH), 5% talk	479	OK	Critical	Very critical
4 hours in open space office (1,000 m^3, 1 ACH), 5% talk	24	OK	OK	OK
4 hours in open space call centre (1,000 m^3, 1 ACH), 60% talk	100	OK	OK	Borderline
2 hours in meeting room (100 m^3, 3 ACH), 50% talk, 5% loud	390	OK	Critical	Very critical
30 minutes in small shop / boutique (100 m^3, 3 ACH), 20% talk	451	OK	Critical	Very critical
2 hours in restaurant (500 m^3, 1 ACH), 20% talk, emitter no mask	153	OK	OK	Critical
2 hours in disco (300 m^3, 3 ACH), 20% loud, 50% heavy dancing, receiver only FFP2	379	OK	Critical	Very critical
1 hour travel by train (57 m^3, 7.1 ACH), 20% talk	40	OK	OK	OK
1 hour travel by train (57 m^3, 7.1 ACH), 20% talk, emitter no mask	180	OK	OK	Critical
30-minute trolleybus ride (100 m^3, 2 ACH), 20% talk, emitter no mask	220	OK	OK	Critical

inhaled aerosols if properly fitted to the face [20, 21]. However, when spending prolonged time in situations with extreme aerosol formation, not even FFP2 respirators may be sufficient, as shown by the scenario of a super-emitter in a disco where very loud voices are required for communication.

In conclusion, our modelling and risk assessment suggest that both higher viral load and increased infectivity are likely to be important contributors to the rapid spread of Delta and Omicron. However, there are more ways by which virus variants may, in principle, affect transmission by aerosols. For example, it is not known to what extent aerosol formation is modified in infected individuals, although altered mucus viscosity can lead to such changes [22, 23]. Also, an increase in viral production near the vocal cords, the place where the most aerosols are produced [24, 25], would likely increase the viral emissions. More research is needed to address such questions.

Use case: When using the tool, it is important to understand that the CO_2 and viral concentrations in a room follow different mathematical processes. CO_2 increases with every additional person. In contrast, the viral concentration follows a stochastic process: it increases only if one of the people in the room is infectious. How much virus can accumulate in a room depends strongly on the emission strength and the activity of the infected person. This can be illustrated by a use example with the tool: a school room for a class of twenty teenagers with a volume of 250 m^3 and mechanical ventilation that provides three outside air exchanges per hour. Let's assume the teacher installs a recirculating air cleaner with a CADR of 500 m^3 h^{-1}. The tool predicts CO_2 concentrations of 640, 760, 810 and 840 ppm after 15, 30, 45 and 60 minutes respectively for 5% light activity. To confirm that the ventilation works, the teacher can use a simple CO_2 monitor to check if the measured time course is in a similar range. CO_2-wise, the room is fine. But what about the viral dose? If everyone wears ill-fitting masks, the room should be fine for Delta but no longer for Omicron, especially when considering that they have several classes per day. If everyone wears well-fitted surgical masks, the situation still seems safe. However, an entire singing class would not be advisable because it would require very well-fitted FFP2 respirators to stay below the critical dose, if this is set to 100 virus copies (which would be reached after four minutes if no masks are worn). Therefore, the activities in the classroom should be carefully assessed before they are performed. For those activities that still seem safe, the CO_2 time course then indicates whether the ventilation is performing as needed for that activity.

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Conflicts of interest

All authors have completed and submitted the International Committee of Medical Journal Editors form for disclosure of potential conflicts of interest. No potential conflict of interest was disclosed.

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