**Supplemental Material**

**Quantitative Microbial Risk Assessment for Airborne Transmission of SARS-CoV-2 via Breathing, Speaking, Singing, Coughing, and Sneezing**

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S1. Selection of expelled particle number and size distribution data

Hugely varying ranges of number of aerosol particles expelled by expiratory activities are reported in the literature. Here we discuss more in-depth the available data and the choices that were made for the data selected for this study. In the selection of data from the literature, studies concerning bacterial infections were not included, as bacteria are typically much larger than viruses. Table S1 gives an overview of the size distribution data used for the different scenarios in this study, showing the counted droplet diameter ranges, the employed method, and the health status of the investigated subjects.

Table S1. Overview of the size distribution data used for the different scenarios in this study

| Scenario       | Reference               | Counted droplet diameter ranges | Counting method                                                                 | Investigated subjects        |
|----------------|-------------------------|---------------------------------|---------------------------------------------------------------------------------|-------------------------------|
| Breathing      | Fabian et al. (2011)    | 0.3 - >10 μm                    | Optical particle counter                                                        | Human rhinovirus-infected    |
| Speaking Low   | Asadi (2019)            | 0.5 – 20 μm                     | Aerodynamic particle sizer, TSI model 3321                                      | Healthy                      |
| Speaking High  | Duguid (1946)           | 0.25 – 20 μm                    | Impaction and counting under a microscope                                       | Healthy                      |
| Singing        | Alsved et al. (2020)    | 0.5 – 10 μm                     | Aerodynamic particle sizer, TSI model 3321                                      | Healthy                      |
| Singing        | Mürbe et al. (2020)     | 0.3 - >10 μm                    | Laser particle counter (Lighthouse Solair 3100 E, Lighthouse Worldwide Solutions, Fremont (CA)) | Healthy                      |
| Coughing Low   | Lindsley et al. (2012)  | 0.35 to 10 μm                   | Laser aerosol particle spectrometer                                             | Influenza virus-infected     |
| Coughing High  | Duguid (1946)           | 0.25 – 20 μm                    | Impaction and counting under a microscope                                       | Healthy                      |
| Sneezing Low   | Gerone et al. (1966)    | <1 – 15 μm                      | Large funnel with a particle-size analyser based on light-scattering (Mumma et al. 1962) | Coxsackie virus-infected     |
| Sneezing High  | Duguid (1946)           | 0.25 – 20 μm                    | Impaction and counting under a microscope                                       | Healthy                      |

Breathing

Only one study was identified that reported both counted particle numbers and their size distribution in the range 0.3 - 20 μm for breathing, the work by Fabian et al. (2011), allowing for calculation of exhaled volumes of aerosolized droplets. This study employed an optical particle counter for six size bins and measured during normal tidal breathing for human rhinovirus-infected subjects. Fabian et al. found that HRV-infected subjects exhaled from 0.1 to 7200 particles / L of exhaled air during tidal breathing. The data in Figure 5 of Fabian et al. were extracted using a plot digitizer https://apps.automeris.io/wpd/ and used as the basis for this study. The median concentration determined from this figure was ~15 particles / L.

Several other studies on particle emission during breathing were considered (Edwards et al. 2004; Fabian et al. 2008; Johnson and Morawska 2009; Leung et al. 2020; Papineni and Rosenthal 1997). All these studies were found not to contain suitable data that could be used to calculated exhaled volumes of aerosolized droplets, but they reported results that are generally in line with the data from Fabian et al. (2011), giving confidence in the approach taken in this study.
Fabian et al. (2008) studied exhaled breath in influenza-infected subjects using an optical particle counter. They reported that concentrations ranged from 67 to 8,500 particles / L of air. The results were reported for four size bins, concentrations in the various bins ranged from 61 - 3848 / L (particles between 0.3 - 0.5 µm), 5 - 2756 / L (0.5 - 1 µm), 1 to 1916 / L (1 - 5 µm), and 0 to 9 / L (>5 µm). Only ranges were reported by Fabian et al. (2008); however, these ranges were similar, if not somewhat higher, than those used in Fabian (2011). As Fabian et al. (2011) reported for six size bins and also reported quantiles and medians, the data by Fabian et al. (2011) were more suitable for calculations. Papineni and Rosenthal (1997) reported exhaled particle counts for two size bins (<1 and >1 µm) in exhaled breath of healthy human subjects. From Table 2 in Papineni and Rosenthal, the mean observed counts were 12.5 and 4.7 particles < 1 µm / L for mouth and nose breathing, respectively, and 1.9 and 0.7 particles >1 µm / L for mouth and nose breathing, respectively. The mouth breathing mean count was very similar to the median found by Fabian et al. (2011). Papineni and Rosenthal reported that their optical particle counter detected particles of >0.3 µm, but the upper end of the size range is unclear, and only two size bins were used, which does not allow for volume calculations. Johnson and Morawska (2009) employed an aerodynamic particle sizer, the EDIS system, for counting particles of 0.5 – 20 µm in exhaled breath in healthy subjects. The Johnson and Morawska particle counts were not reported for different size classes, and thus did not allow for the volume calculations that were necessary for our study. However, Figure 7 contains data on the total concentration of particles in exhaled breath, and these were extracted using the abovementioned plot digitizer. The average observed particle concentration from this figure was calculated to be ~250 particles / L, which is approximately one order of magnitude higher than the median of Fabian et al., but well within the range found by Fabian et al. (2011). Edwards et al. (2004) employed an optical particle counter for exhaled particles >150 nm in healthy subjects. They reported that the number of exhaled particles / L varied dramatically over time and among subjects, ranging from a low of one particle / L to a high of >10^4 particles / L, so a similar, if slightly wider, range than Fabian et al. (2011). However, Edwards et al. did not report particle counts for the exhaled breath of human subjects for different sizes classes, thus not allowing for volume calculations. Leung et al. (2020) reported experiments on particle counts in breath collected for half an hour during which participants also coughed. Leung et al. measured in subjects infected with different viruses, among which was a coronavirus (not SARS-CoV-2). For the coronavirus-infected subjects, Leung et al. reported up to 10^5 particles <5 µm per breath sample (collected for 30 minutes)(Leung et al. Figure 1a). Assuming a tidal breathing rate of ~7 L / minute, this would mean up to ~500 particles / L exhaled breath, which is approximately one order or magnitude lower than the maximum of the range observed by Fabian et al. (2011). The relative contribution of breathing and coughing could not be deducted from the Leung et al. data, making these unsuitable for our purposes.

**Speaking**

The numbers and size distributions or aerosol droplets expelled by speaking were from Duguid (1945, 1946) and Asadi et al. (2019).

Asadi et al. employed an aerodynamic particle sizer (APS, TSI model 3321) on exhaled breath during speaking of healthy subjects into a funnel in a laminar flow hood. The subjects were asked to read aloud a passage from a book. Figure 4B concentration data in particles / cm³ of Asadi et al. (2019) was digitized using the abovementioned plot digitizer. The average particle concentration in exhaled breath was 2.0x10^2 (6.0x10^1 – 8.4x10^2) particles / L. These numbers were scaled to the volume of air a person exhales during speaking a minute using the values for tidal breathing increased by 13.5%
Bunn and Mead 1971). Recovering stain-containing droplet-nuclei from the air onto oiled slides by a slit sampler and counting them under a microscope, Duguid (1945, 1946) counted particles in the initial size range of 0.25 µm to 20 µm. For speaking, Duguid had subjects counting loudly from 1 to 100 and measured at a distance of 1.5 feet from the mouth, and found $2.5 \times 10^2$ (5.0$\times 10^1$ – 7.7$\times 10^2$) expelled droplets (Table IV from Duguid (1945)). It was assumed that counting from 1 to 100 represented an observed speaking time of 1.5 minutes. Duguid reported underestimation of particles less than about 1 µm with highest counts around 2-4 µm. In contrast, Asadi counted particles between 0.5 – 20 µm with highest counts around 1 µm (Asadi et al. 2019).

The size distribution data were, for the Speaking Low scenario, from Asadi (2019), and for the Speaking High scenario from Duguid (1946). For Asadi, the size distribution was sampled from the data in Figure 3D for normal speaking, digitized using the abovementioned plot digitizer. For Duguid, the size distribution was sampled from Table 2 for speaking loudly.

Several other studies on particle emission during speaking were considered (Chao et al. 2009; Loudon and Roberts 1967; Papineni and Rosenthal 1997), that were excluded for several reasons. The work by Papineni and Rosenthal (1997) on speaking was excluded for the same reason it was excluded for breathing. Papineni and Rosenthal reported that their optical particle counter detected particles of >0.3 µm, but the upper end of the size range is unclear, and only two size bins were used, which does not allow for volume calculations. For both breathing and speaking it was observed that studies which looked specifically at smaller size ranges of ~0.5 to 10 or 20 µm, e.g. (Asadi et al. 2019; Fabian et al. 2011), found highest particle counts in the smallest bins around 1 µm. In contrast, studies that measured over a larger size range (up to ~2000 µm) e.g. (Chao et al. 2009; Loudon and Roberts 1967), reported highest particle counts between 10 and 20 µm and decreasing particle counts in smaller bins. Chao et al. (2009) noted in their discussion that the IMI detection system they employed had a lower detection limit of about 2 µm and that this contrasted with other studies that observed peaks in smaller particles, suggesting that the IMI system may not cover the entire size range of expelled particles. As we were specifically interested in the smaller particles that can stay airborne, we chose not to include the data generated by Chao et al. (2009) and Loudon and Roberts (1967), as these were likely underestimating the numbers of particles expelled in the smaller size bins.

**Singing**

For the size distribution of aerosols expelled by singing the 1-minute loud singing data of Alsved et al. (2020) were used. The particles were smaller than 5 µm, with a peak around 1.2 µm. A similar distribution was observed by Asadi et al. (2019) for speaking. Mürbe et al. (2020) confirmed that higher emission rates of aerosols were produced during singing in comparison to speaking and breathing. Loudon and Roberts (1968) found that fewer aerosols were expelled by singing than by talking, which is surprising. Because Mürbe et al. (2020) provided good estimates of aerosol numbers and Alsved’s size distribution data were consistent with other studies, these data were selected to calculate the volume of expelled aerosols by singing.

**Coughing**

Hugely varying ranges of number of aerosol particles expelled by coughing were reported in literature. For a lip-cough, Duguid (1945) reported $4.8 \times 10^3$ (4.9$\times 10^2$ – 1.6$\times 10^4$) particles and for a tongue-teeth cough, $8.2 \times 10^3$ (1.5$\times 10^3$ – 5.2$\times 10^4$) particles. Gerone et al. (1966) reported that a representative cough contained $9 \times 10^3$ particles in the size range of less than 1 µm to 15 µm, which corresponded to 200 picolitre (pL). Lindsley et al. (2012) reported that for patients with influenza, their average cough aerosol volume was 38.3 pL of particles per cough (SD 43.7); after patients
recovered, the average volume was 26.4 pL per cough (SD 45.6). The number of particles produced per cough was also higher when subjects had influenza (average 7.5×10⁴ particles/cough, SD 9.7×10⁴) compared with afterward (average 5.2×10⁴, SD 9.9×10⁴), although the difference did not reach statistical significance. The average number of particles expelled per cough varied widely from patient to patient, ranging from 9×10² to 3.0×10⁵ particles/cough while subjects had influenza and 1.1×10³ to 3.1×10⁵ particles/cough after recovery. Lindsley et al. (2012) enumerated particles with a size range of 0.35µm to 10 µm with a laser aerosol particle spectrometer. Yang et al. (2007) detected on average 1000 to 2000 droplets/mL with the more droplets when a person was older, which two orders of magnitude higher than the reported number of droplets/mL.

In the quantitative microbial risk assessment (QMRA), the logarithm of the number of droplet nuclei from a cough of particles less than 20 µm was simulated as a normal distribution with mean 4.8 and standard deviation 0.35 (Table 2 of the main text).

Also, a wide range in particle size distributions in coughs was reported in literature. Lindsley et al. (2012) measured particles in the range of 0.35 µm – 4 µm, whereas Zayas et al. (2012) reported 0.12 µm – 0.8 µ. Zayas et al. (2012) enumerated particles two orders of magnitude more than others. Zayas claimed that previous studies had limited resolution in the submicrometer ranges or were biased due to sampling air stream. Of the 45 investigated persons, Zayas et al. (2012) identified 10 persons as high emitters with one standard deviation of the number of particles higher than average. One high emitter with particle numbers that were two standard deviations higher was excluded.

Sneezing

Recovering stain-containing droplet-nuclei from the air onto oiled slides by a slit sampler and counting them under a microscope, Duguid (1945) counted particles in the initial size range of 0.25 µm to 20 µm. For a natural sneeze, Duguid (1945) reported 1.1×10⁶ (6.5×10⁴ – 3.1×10⁶) particles and for a simulated strong sneeze, 9.3×10⁶ (1.5×10⁶ – 3.0×10⁷). Gerone et al. (1966) captured expelled particles using a funnel and reported that a representative sneeze contained 1.6×10⁶ particles in the size range of less than 1 µm to 15 µm, which corresponded to 6000 pL. In the QMRA, the logarithmic of the number of droplet nuclei from a sneeze of particles less than 20 µm was simulated as a normal distribution with mean 6.1 and standard deviation 0.22 (Table 2 in the main text).

As for size range, Gerone et al. (1966) counted relatively more smaller particles than Duguid (1946). Duguid found fewer smaller particles when measuring at a longer distance, so may have underestimated the numbers of smaller particles due to evaporation. In contrast, Gerone et al. (1966) aimed to capture the complete sneeze, but reported not to have enumerated particles larger than 15 µm.

Han et al. (2013), enumerated sneezed particles with a laser beam at a short distance and found that the size distribution from about half of the tested persons enumerated sneeze was bimodal, but even the size range of the smaller part of this distribution consisted of particles larger than 20 µm. Possibly, in the narrow laser beam, a large part of the sneeze was missed.
Table S2. Total aerosol droplet volumes from 20 minutes of breathing, speaking or singing, one cough or one sneeze (picolitres) (see figure 2 main text)

|          | Mean | Min | Max | 5%  | 50% | 95% |
|----------|------|-----|-----|-----|-----|-----|
| Breathe  | 44.  | 0.  | 18000. | 0.11 | 5.9 | 120. |
| Speak-Lo | 250. | 9.5 | 2100. | 61.  | 200. | 630. |
| Speak-Hi | 350. | 11. | 3400. | 86.  | 280. | 880. |
| Sing     | 4300. | 310. | 41000. | 1100. | 3400. | 10000. |
| Cough-Lo | 47.  | 1.3 | 690.  | 9.5  | 34.  | 130. |
| Cough-Hi | 4900. | 130. | 66000. | 930. | 3600. | 13000. |
| Sneeze-Lo| 5500. | 700. | 32000. | 2100. | 4600. | 11000. |
| Sneeze-Hi| 48000. | 5600. | 210000. | 15000. | 35000. | 80000. |

Table S3. Numbers of SARS-CoV-2 RNA copies expelled after 20 minutes of breathing, speaking or singing, one cough or one sneeze with a concentration of $10^8$ RNA copies /mL in the mucus (see figure 3 main text)

|          | Mean | Min | Max | 5%  | 50% | 95% |
|----------|------|-----|-----|-----|-----|-----|
| Breathe  | 1100. | 0.  | 450000. | 3.  | 150. | 3200. |
| Speak-Lo | 6000. | 229. | 53000. | 1600. | 5200. | 16000. |
| Speak-Hi | 9100. | 290. | 86000. | 2200. | 7300. | 23000. |
| Sing     | 110000. | 7900. | $1 \times 10^6$ | 29000. | 87000. | 260000. |
| Cough-Lo | 3500. | 110. | 460000. | 630. | 2200. | 8500. |
| Cough-Hi | 250000. | 11000. | $3.3 \times 10^6$ | 47000. | 180000. | 670000. |
| Sneeze-Lo| 260000. | 35000. | $1.6 \times 10^6$ | 100000. | 230000. | 530000. |
| Sneeze-Hi| $2 \times 10^6$ | 280000. | $1.1 \times 10^7$ | 770000. | $1.7 \times 10^6$ | $4 \times 10^6$ |
Computational tool *AirCoV2* is coded in Mathematica version 12.0.0 (Wolfram Research Inc. 2019) using the model as described in equations 1 -13 in the main text. Using room dimensions, ventilation, exposure time, virus concentration in mucus and virus infectivity as inputs (see left dashboard in the screenshot of *AirCoV2* in figure S1) to compute virus concentration in the air, the dose and risks of illness for the breathing, speaking, singing, coughing and sneezing scenarios.

The tool is freely available and can be obtained by contacting the corresponding author.

Figure S1 Screenshot of interactive computational tool *AirCoV2* for a room of 100 m3, and exposure of 2 hours and a ventilation rate of 6/h.
Literature

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