Statistical data analysis of expiratory droplet mass during talking and prediction of SARS-CoV-2 number concentrations using dispersion models

Hitoshi Kono [1) 2)]

1) Professor Emeritus at University of Hyogo, 2) Japan Meteorological Corporation

Abstract

In order to investigate droplet nuclei infection, diffusion models are used to calculate the number concentration of SARS-CoV-2 in expiratory droplets during conversation in indoor and outdoor settings. Measurement data from published papers on the diameters and masses of droplets emitted during conversation are analysed to obtain a reliable mean for the prediction. The 95% confidence interval for the population mean of the released expiratory droplet mass in droplets of size 100 μm or less falls within a relatively small variation of 0.5 to 1.5 times the sample mean. The cut-off diameter is set in the range of 70–100 μm indoors and 70–130 μm outdoors, depending on the relative humidity. The virus number concentration is calculated and the relationship between the number of viruses inhaled by breathing and the ventilation rate of the room is studied. The ventilation rate is represented by the CO_2 concentration in the room. When one super-spreader speaks in a room for 1 hour, the calculated result is that the dose of the virus inhaled in 1 hour exceeds the infection threshold, even if the ventilation volume in the room is very high. In this case, most of the people in the room will be infected. These predictions are consistent with previously reported infection data that transmission occurs indoors and are rare outdoors.

Keywords; SARS-CoV-2, dispersion model, expiratory droplet, number concentration, infection, ventilation

Author's e-mail: koyubi@sensyu.ne.jp

1. Introduction

"Droplet transmission" refers to the transmission of a virus immediately after the release of relatively large exhaled droplets within a short distance of 1 m. "Droplet nuclei transmission" refers to transmission that occurs through the inhalation of a virus or fine droplets containing the virus that have been floating in the room for a long time. It has recently been noted that SARS-CoV-2 causes not only expiratory droplet transmission but also droplet nuclear transmission via fine expiratory droplets and

droplet nuclei [1].

(Note) The droplet nucleus is a dry residue that remains after the water content of a droplet has evaporated. The final equilibrium size of the droplet is determined by the ambient relative humidity. These droplets may contain the virus.

Tentative standards have been issued for indoor ventilation to avoid SARS-CoV-2 droplet nuclear transmission, but the relationship between transmission and ventilation volume has not yet been clarified [2] [3].

In this paper, dispersion models are used to calculate the number concentration of SARS-CoV-2 indoors and outdoors during conversation for droplet nuclei transmission. This prediction is important as it provides the basis for examining transmission thresholds. From the calculated concentration results and reported transmission data, the effects of the ventilation rate of the room and social distancing outdoors on transmission are examined. Droplet release is a feature of conversation, coughing and sneezing, but the focus of this work is on expiratory droplets from conversation alone. Li et al. [4] have already performed calculations for the diffusion of droplets exhaled during coughing. Oliveira et al. [5] calculated the dispersion of expiratory droplets during conversation. However, dispersion predictions based on detailed mass analysis results of expiratory droplets during conversation have not yet been performed. The total mass of aerosol exhaled during respiration is much smaller than the mass of expiratory droplets during conversation. To predict the virus number concentration, data on the number of expiratory droplets as a function of diameter and the number of viruses in these expiratory droplets are required.

Although there are a lot of measurement data available on the number distribution of droplets as a function of droplet size, there are not a lot of data that measure the total number of droplets released. Typical sources of data measuring the total number by droplet size include Loudon and Roberts [6], Duguid [7], and Xie et al. [8]. Details of this expiratory droplet data are given in Chapter 3.

Droplets of large size quickly fall to the ground, but fine droplets, aerosols and droplet nuclei float in the air for a long time. Much research has been carried out on the size range of expiratory droplets that float in the air for a long period [5, 9–11]. The details of these works will be described in Chapter 2.

Since there have been many measurements of the SARS-CoV-2 abundance in expiratory droplets [12, 13], these measurements are used in the dispersion calculation.

The number of viruses required to induce infection with COVID-19 (that is, the infectious dose) was estimated by Prentiss [14] and Karimzadeh et al. [15], and was also reviewed by the Usher Institute [16]. Since then, the infectivity of the SARS-CoV-2

variants has continued to change. However, this paper compares the infectious dose of SARS-CoV-2 with the calculated inhaled virus dose, limited to previously published papers.

2. Sizes of droplets floating in the air for a long time—the cut-off diameter

Fine droplets fall due to gravity, but are acted on by the drag force in air, with the gravity W (N) and the drag force D (N) balancing each other out to reach a constant velocity (terminal velocity) U (m s^{-1}). The buoyancy is as small as 1/1000 of the gravitational effect, so it can be ignored. The gravity W acting on a spherical particle with radius r is given by Equation (1):

$$W = \frac{4}{3}\pi r^3 \rho_m g \qquad (1)$$

where ρ_m (kg m^{-3}) is the particle mass density and g (m s^{-2}) is the gravitational acceleration.

The drag force D acting on the sphere is given by Equation (2):

$$D = 1/2\, C_D A \rho_a U^2 \qquad (2)$$

where C_D is the drag coefficient, $A = \pi r^2$ (m^2) is the projected area of the sphere, and ρ_a (kg m^{-3}) is the air density.

The drag coefficient is given by the Stokes equation resistance coefficient (3) (4) when the Reynolds number $Re < 1$:

$$C_D = 24 / Re \qquad (3)$$

$$Re = \frac{U \times d}{\mu / \rho_a} \qquad (4)$$

where μ (Pa·s) is the viscosity coefficient of air and $d = 2r$ (m) is the diameter of the sphere.

When $Re < 1$, the terminal velocity (5) is obtained from Equations (1) to (4).

$$U = \frac{2r^2 \rho_m g}{9\mu} \qquad (5)$$

When $Re > 1$, there are many empirical formulas for the drag coefficient, but here Equation (6) is used [17] with $1 < Re < 5$ (the water droplets have a size of 200 μm or less), which shows only a small error relative to experimental values.

$$C_D = \left\{ \sqrt{\frac{24}{Re}} + 0.5407 \right\}^2 \qquad (6)$$

The terminal velocity in Equation (7) is derived from Equations (1), (2), (4) and (6).

$$U = \left(\frac{8\pi r^3 \rho_m g}{3 C_D A \rho_a} \right)^{1/2} \qquad (7)$$

Figure 1 shows the terminal velocities of the water droplets (density ρ_m = 1000 kg m^{-3}) obtained from Equations (5) and (7). The terminal velocity of a water droplet of size 20 µm is 1 cm s^{-1}, and for a size of 10 µm it is about 3 mm s^{-1}. It is known that fine droplets with small terminal velocities have low inertia, and they therefore follow the movement of the air and float for a long time.

The range of droplet sizes that float for a long time differs for outdoor and indoor scenarios. The outdoor atmosphere usually has a turbulent flow, except in the case of strong stable conditions when there is a ground inversion layer of temperature. In urban areas, turbulence caused by airflow passing through buildings predominates near the ground, so the atmospheric stability is neutral. In such a flow, fine droplets follow the movement of the air and are forcibly mixed, so that they float in the atmosphere for a long time. It is known that cedar pollen floats for a long time, but with a diameter of d = 30–40 µm, the density is ρ_m = 0.86 × 10^3 kg m^{-3}, and the terminal velocity is U = 2.5-4.4 cm s^{-1}. Assuming that the density of water droplets is ρ_m = 1 × 10^3 kg m^{-3}, the droplet size corresponding to the terminal velocity U = 4.4 cm s^{-1} is d = 37 µm. In other words, in atmospheric turbulence, water droplets with an aerodynamic diameter of about 35 µm or less float in the atmosphere [18].

For the indoor scenario, consider as an example that the ceiling of a large room with a volume of about 700 m^3 has an air conditioner fan outlet and inlet. It is assumed that the mixing time of the indoor air by the fan is sufficiently shorter than the replacement time of the indoor and outside air, and the indoor air is uniformly mixed. In general, the flow velocity in the room is small, and if the representative flow velocity is $U \approx$ 0.1 m s^{-1} and the typical length is $L \approx$ 0.5–1 m, the Reynolds number is $Re \approx$ 3500–7000, which is near the transition region from laminar to turbulent flow. The mixing effect due to turbulent flow is small. Therefore, it is assumed that droplets emitted from a height of 1.5 m indoors fall to the floor at terminal velocity depending on the droplet size. The floating time is the time it takes the droplets to fall to the floor.

It is known that the smaller the water droplet, the higher the evaporation rate. This is

called the Kelvin effect or the curvature effect. For example, a water droplet with a relative humidity of 60% and a diameter of 100 μm evaporates in 20 s, and a water droplet with a diameter of 10 μm evaporates in 0.2 s [10].

Wells [9] first presented the relational expression between the diameter of a droplet (of pure water) dropped from a height of 2 m and the evaporation time. Xie et al. [11] solved for the reduction in the droplet size by evaporation and the droplet equation of motion at the same time. Their results show that at a room temperature of 18 °C and a relative humidity of 90%, droplets with a diameter of 60 μm or less emitted from a height of 2 m evaporate before falling to the floor. At 0% relative humidity, droplets with a diameter of 125 μm or less evaporate before falling to the floor.

On the other hand, when droplets are mixed with NaCl, protein and surfactant, the evaporation rate is lower than that of pure water [19]. It has been reported that in an environment with a relative humidity of 20 to 80%, the ratio of the final diameter d to the initial diameter d_0 converges to 20% or 40% for a protein concentration of 3 mg mL^{-1} (low concentration) and 76 mg mL^{-1} (high concentration), respectively [20]. Oliveira et al. [5] calculated the evaporation and falling times when droplets were mixed with protein and salt. According to the evaporation-landing time calculated by Oliveira et al. [5], droplets released from a height of 1.5 m from the floor fall to the floor if the size is 100 μm or more at a relative humidity of 40%, but droplets with a diameter of 100 μm or less evaporate before reaching the floor and become droplet nuclei. In addition, since the evaporation rate slows down at a relative humidity of 80%, those droplets with a size of 70 μm or more fall to the floor, but water droplets with a size of 70 μm or less evaporate before reaching the floor and become droplet nuclei. Here, at a temperature of 20 °C and a relative humidity (RH) of 40%, 60% and 80%, the evaporation-landing times were calculated for two droplet components: low protein sputum (9 mg / mL NaCl, 3 mg / mL protein) and high protein sputum (9 mg / mL NaCl, 76 mg / mL protein). In this paper, a value for the shrink rate of 27% is used for the low-concentration protein as in the nasal surface airway fluid of Oliveira et al. [5]. This value is close to 30% of the average shrink rate of the high- and low-concentration proteins of Marr et al. [19] mentioned above. The cut-off diameter of expiratory droplets contributing to droplet nuclei infection is assumed to be 70 μm to 100 μm in the range of 80% to 40% RH. To calculate outdoor diffusion, the mass of droplets with a size of 100 μm or less is input into the diffusion models. Since the final equilibrium diameter due to evaporation is 27 μm or less based on the previous shrink rate, such a droplet is expected to be suspended outdoors for a long time.

Inside a room, on the other hand, the terminal velocity differs depending on the droplet

size, and the floating time differs, so the floating time is given as shown in Appendix Table 1.

3. Analysis of measurement data for expiratory droplets during speech

3.1 Method

There have been numerous measurements of the distributions of droplet sizes exhaled during speech. Han et al. [21] reviewed these. However, there are not a lot of data that measure the total amount of droplets exhaled. Typical data sets measuring the total amount of expiratory droplets are those provided by Loudon and Roberts [6] (abbreviated as L & R), Duguid [7] and Xie et al. [8] (abbreviated as Xie). In their experiments, the subjects count loudly from 1 to 100 in English and the expiratory droplets during that time are measured. (In this paper, it is assumed that counting from 1 to 100 took 100 seconds. [22]) To sample the total mass of expiratory droplets, slips of paper or microscope glass slides or slips of water-sensitive paper are placed inside a box, and the subject talks through a hole into the box. After the experiment, the droplet sizes and the number of droplets attached to the glass or paper slides are counted using a microscope. This is called the solid impaction method [21].

In the solid impaction method, small floating droplets or droplet nuclei are not measured, and therefore the number of small droplets and droplet nuclei is underestimated. Chao et al. [23] corrected the L & R measurements using droplet size distribution data measured using the Interferometric Mie Imaging (IMI) method (Appendix Table 2). IMI can be measured for a range of droplet sizes from 2 to 2000 μm. The corrected value is abbreviated as L & R-IMI.

Xie investigated the effect of food dye on droplet generation. For a total mass of droplets with a size of 100 μm or less, the number of droplets released was halved when food dye was not used. Therefore, in this paper, the mass of droplets without food dye is used for concentration prediction. Xie also studied the amount of evaporation from the point of release to when the droplets attach to glass slides or strips of water-sensitive paper, but the amount of evaporation was about 10% of the total mass with a droplet size of 100 μm or less, which is low. Therefore, this difference can be ignored in the concentration prediction.

In this paper, the droplet data are analysed using the following method.

A volume or mass distribution graph for each droplet size is drawn, and the total volume or total mass with a size of 150 μm or less to 70 μm or less is compared.

The standard deviations of the mass distributions for different experimental data sets (researchers) and subjects are statistically compared.

The principles, effective measurement range and measurement accuracy of the multiple measurement methods are compared. The particle measurement methods are summarised in Appendix Table 2 [24–27].

The expiratory droplet data used in the analysis are shown in. Supplementary material 1

3.2 Results and discussion

Table 1 shows the measured data for the expiratory droplet mass by droplet size. The measurements are by Loudon and Roberts (L & R), Duguid , Xie and Chao et al. [23]. L & R-IMI is the correction of the L & R data carried out by Chao et al. using the IMI method. L & R used food dye in their experiment, but here the corrected value for when food dye is not used is calculated. This calculation uses a correction factor of about 1/2 obtained from Xie's experiment.

Figure 2 shows the total volume of expiratory droplets released during speech by droplet size. From Figure 2, it can be seen that: (1) There is a large difference between the solid impaction method and the IMI method for droplets with a size of 30 μm or less. The IMI method accurately measures even small droplets of 2 μm (Appendix Table 1). (2) Comparing the volume distributions of L & R and Xie (with food dye), the values are very close. These two can be regarded as measured data from the same group. In contrast, the measured data obtained by Duguid are far from these two. (3) Droplets with a smaller diameter have a smaller contribution to the total mass. According to the data by L & R-IMI, the droplet size that makes up 90% of the mass for droplets of diameter 100 μm or less is in the range of 30 μm to 100 μm. In addition, the droplet size that makes up 90% of the mass for droplets of diameter 75 μm or less is in the range of 25 μm to 75 μm.

Table 1 shows the mass (by size) of droplets exhaled while counting loudly from 1 to 100 in 100 seconds. The columns in the table are the total mass of expiratory droplets and the total mass below the cut-off diameters. The cut-off diameters are 150 μm, 130 μm, 100 μm and 75 μm. In a room, the cut-off diameter is 100 μm or less at a relative humidity of 40%, and the cut-off diameter is 75 μm or less at a relative humidity of 70%. The number of experiments n, the mean and standard deviation σ_{n-1}, and the coefficient of variation C.V. (%) for each experimental data set are shown. Outdoors, the cut-off diameter can extend to around 130 μm.

The procedure for obtaining the mean value from data in which the number of measurements is small and varies greatly depending on the researcher is shown below.

Since the value of Duguid in Table 1 is very small compared to the values provided by

the other measurers, Duguid is excluded from the calculation of the following mean value.

The total mass differs by a factor of around 10 between L & R and Xie. The total mass of expiratory droplets attached to a surgical mask was also measured by Xie. The droplet mass measured on the surgical mask is close to the value from L & R's data. From this, it can be seen that the total mass of droplets found, including for large droplet sizes (100 μm to 1000 μm), varies greatly depending on samples.

However, it is important to note that the mass variation among experimenters is relatively small for diameters of 150 μm or less, 130 μm or less, 100 μm or less and 75 μm or less. The mean and the standard deviation of masses for these droplet size ranges are now analysed. First, note that the mean values of the data using food dye from L & R and from Xie are close. These two sets of data were treated as being one group, and the interval estimation of the population mean was performed for a 95% confidence level. As a result, the population mean of droplet masses with a size of 150 μm or less is within ± 30% of the sample mean, that with a size of 100 μm or less is within ± 1/4 of the sample mean, and that with a size of 75 μm or less is within ± 1/2 of the sample mean [Table 1 (1) + (4)]. From this result, it was decided that L & R and Xie can be treated as a single group of data and their mean values are representative.

The mean value of the data without using food dye was examined. Interval estimation of the population mean for a 95% confidence level was performed for Xie and L & R without dye [Table 1 (1a) + (3) mean]. As a result, the population mean of droplet masses with a size of 150 μm or less is within 0.6 to 1.4 times the sample mean, and that with a size of 100 μm or less is within 0.5 times to 1.5 times the sample mean, respectively. The solid impaction method underestimates suspended droplets of 30 μm or less. However, when estimating the total mass in the ranges of droplet sizes of 150 μm or less to 75 μm or less, the data from the solid impaction method can be used approximately because the mass ratio of large droplets of 30 μm or more to the total mass is high.

The air stream in the room is assumed to be laminar flow. Accordingly, the diameter of particles that can float for a long time is smaller than outdoors. The mass contribution of fine droplets with a size of 30 μm or less is now about 40% of the total mass, which cannot be ignored. Therefore, L & R—IMI data was used to accurately measure even small droplets to 2 μm, where the correction for the effect of the dye was made (Table 1-1c).

As for the variation among individuals, the coefficient of variation of the measured value of L & R is about 30%, and that of Xie is around 50 to 150%. Therefore, the

average coefficient of variation among individuals is considered to be about 100%. The maximum value is assumed to be the mean value + 3σ (99.9% value of the Gaussian distribution) and is evaluated to be about 4 times the mean value. The data considered this time are the amount of expiratory droplets released when counting from 1 to 100 in English, but it has been pointed out that there may be differences depending on the language [28]. Therefore, it is necessary to increase the experimental data for various languages in the future.

<Droplets released during breathing>

Droplets released during breathing normally have a particle size smaller than 1 μm [21]. When the particle size is reduced to 1/10, the volume and mass are both 10^{-3} times smaller. Comparing particle sizes of 100 μm and 1 μm, the volumes and masses of the latter are 10^{-6} times that of the former.

Asadi et al. [29] measured droplets emitted during breathing using the Aerodynamic Particle Sizer or APS method. The APS method has high measurement accuracy, but the measurement range is limited to fine particles with a particle size of 0.5 to 20 μm. The average number was 0.1–0.2 s^{-1}, and the particle size was 1 μm or less. This experiment does not sample the total number of particles, but it is assumed that at least 10% of the total particles are sampled. Assuming that the representative particle size is 1 μm, the total mass is of the order of 10^{-10} mg s^{-1}. This value is 10^{-6} times less than the total mass of droplets with a diameter of 100 μm or less, 0.00078 mg s^{-1}, which is released during speech. This is not an amount that leads to infection. In addition, the number of viruses released over 30 minutes was found to be almost zero in data obtained by measuring the number of viruses released during respiration from patients who did not actually cough [30].

4. Calculation using dispersion models

4.1 Method

4.1.1 Virus emission rate

The number of viruses in throat swabs and sputum depends on the number of days after symptom onset [12], and varies depending on the individual. According to a paper by Yang et al. [13], the viral load in saliva of the top 10% of all infected persons was $n_0 = 10^8$ virion mL^{-1} (= virion g^{-1}), and the viral load in saliva of the top 2% was $n_0 = 10^{10}$ virion mL^{-1} (= virion g^{-1}). Given the mass of exhaled droplets within the cutoff diameter during speech as S (g s^{-1}), the virus release rate Ns (s^{-1}) is

$$N_s = n_0 \times S \quad . \qquad (8)$$

When calculating the 1-hour average concentration in the room, the amount of expiratory droplets released is given for each droplet size of 100 μm or less. Appendix Table 1 shows the data used for the calculation.

Outdoors, droplets with an aerodynamic diameter of about 35 μm or less and those with a terminal velocity of 4 cm or less float for a long time due to the large mixing effect of atmospheric turbulence. Therefore, considering the shrinkage of droplets due to evaporation, the initial cut-off diameter is considered to be about 130 μm for RH 40%. The mean value of the droplet mass S is 0.00078 mg s^{-1} (Table 1) with a diameter of 100 μm or less used in the outdoor virus number concentration calculation. The release of droplets during conversation is assumed to be continuous for 1 hour.

4.1.2 Calculation of the number of viruses inhaled from the nose and mouth

This section explains how the number of viruses inhaled by breathing was calculated. The number of inhaled viruses per hour during conversation N_{in} (h^{-1}) was calculated by multiplying the virus number concentration C_v (m^{-3}) by the average respiratory volume of Japanese adults. The average breathing volume of Japanese adults is B = 0.6 m^3h^{-1} when sitting indoors and 0.91 m^3h^{-1} when standing outdoors [31].

$$N_{in} = C_v \times B \qquad (9)$$

4.1.3 Decay of viral activity

This section describes the time decay of virus numbers. Exponential decay is used from the measured data for the time decay of the number of viable viruses N_v in the aerosol.

$$\frac{dN_v}{dt} = -\lambda N_v \qquad (10)$$

The decay coefficient λ is 0.61 h^{-1} [32] and the half-life is 1.1 hours.

Using this formula, the virus count after 1 hour is reduced by 54% of the initial value.

4.1.4 Indoor diffusion model

A single box model is used, and it is assumed that the concentration of droplets exhaled is uniform due to ventilation by the air conditioner. As mentioned in Chapter 2, it is assumed that the flow is close to a laminar flow indoors. The floating time for each particle size is shown in Appendix Table 1. The volume of the room is V_r = 700 m^3, and the height of the ceiling is 2.5 m. It is assumed that there are 30 people in the room, one of whom is COVID-19 infected, and expiratory droplets are continuously released for 1

hour during a conversation. It is assumed that the virus is reduced by ventilation removal, gravity and inactivation. The mass concentrations $C_{m,d}$ (mg m^{-3}) of droplets floating in the room are expressed by Equation (11), where d is the diameter of the droplets. Note that d is the diameter after shrinkage to 27% of the initial diameter due to evaporation immediately after release. Let the total mass of the suspended droplet size d be m_d (mg), so $C_{m,d} = m_d / V_r$, where V_r = 700 m^3 is the volume of the room. Let the mass of droplets released in conversation be $m_{d0,\ gen}$ (mg s^{-1}). The emitted droplet diameter d_0 (μm) is the diameter before shrinkage. The mass concentration is

$$\frac{dC_{m,d}}{dt} = m_{d0,\ gen}/V_r - \{\kappa + (T_{AC})^{-1}\}C_{m,d} \qquad (11)$$

where κ is the gravitational settling rate (s^{-1}). $\kappa = 1/\tau$, where τ (s) is the fall time of expiratory droplets during conversation from a height of 1.5 m to the floor (see Appendix Table 1). T_{AC} (h) is the air change time, with $T_{AC} = 1 / ACH$. ACH is the air change per hour. $(T_{AC})^{-1} = V / V_r$, where V (m^3 h^{-1}) is the ventilation volume of the room.

A steady state for the mass concentration $C_{m,d}$ (mg m^{-3}) is assumed,

$$\frac{dC_{m,d}}{dt} = 0 \ . \qquad (12)$$

The mass concentration $C_{m,d}$ is calculated using Equations (11) and (12). The sum of the droplet mass concentration, C_m (mg m^{-3}), with a particle size of 6 μm to 100 μm is calculated using Equation (13).

$$C_m = \sum_d C_{m,d} \qquad (13)$$

The virus number concentration $C_{v,d}$ (m^{-3}) is expressed by the following equation, where d is the diameter of the droplets containing the virus. Equation (14) adds an attenuation term for viral activity to Equation (13). λ is a constant corresponding to the inactivation rate of the virus, λ= 0.61 h^{-1} = 1.69 × 10^{-4} s^{-1}.

$$\frac{dC_{v,d}}{dt} = N_{v,d0,gen}/V_r - \{\lambda + \kappa + (T_{AC})^{-1}\}C_{v,d} \qquad (14)$$

Let the virus release rate be $N_{v,d0,\ gen}$ (s^{-1}). The virus number concentration $C_{v,\ d} = N_{v,d} / V_r$ (m^{-3}) is assumed to be uniform indoors. A steady state in Equation (14) is assumed for

the virus number concentration, in which the virus release rate $N_{v,d0,\ gen}$ (s^{-1}) and the sum of the three removal processes (ventilation, gravity and virus inactivation) are balanced.

$$dC_{v,d}/dt = 0 \qquad (15)$$

The virus number concentration $C_{v,d}$ is calculated using Equations (14) and (15). The sum of the droplet mass concentrations with a particle size range of 6 μm to 100 μm is calculated using Equation (16).

$$C_v = \sum_d C_{v,d} \qquad (16)$$

The virus number concentration $C_{v,d}$ is calculated using Equation (17).

$$C_{v,d} = n_0 \times 10^{-3} \times C_{m,d} \qquad (17)$$

where n_0 ($mL^{-1} = g^{-1}$) is the number of viruses in expiratory droplets.

The sum of the virus number concentrations C_v with a particle size range of 6 μm to 100 μm is calculated using Equation (18).

$$C_v = \sum_d C_{v,d} \qquad (18)$$

The number of inhaled viruses per hour N_{in} (h^{-1}) in the room is calculated using Equation (9).

(Note) In the field of air conditioning, the CO_2 concentration in a room has often been used as an index for the ventilation rate of a room. In Japan, the ventilation standards for buildings are set in the "Act on Ensuring a Sanitary Environment in Buildings". The standard is "indoor CO_2 concentration 1000 ppm or less" [33].

It is assumed that the per capita CO_2 emissions from exhaled breath are 0.018 m^3h^{-1} (assuming office work), the room volume is 700 m^3 and the number of people in the room is 30. In this case, Appendix Table 3 shows the relationship between the CO_2 concentration and the ventilation volume in the room. The ventilation volume V = 5.8 to 360 ($m^3\ h^{-1}\ person^{-1}$) corresponds to a room CO_2 concentration of 3500 ppm to 450 ppm (in outside air CO_2 = 400 ppm). Here, a 62-fold change in the ventilation volume is assumed. T_{AC} is the time in which the air in the room is replaced by outside air by ventilation.

4.1.5 Outdoor dispersion models

Here, the emphasis is on the diffusion calculation at a short distance (within several tens of meters) from the emission source, and the Gaussian plume model that is typically used for air pollution calculations is used [34]. The Gaussian plume model calculates the hourly average concentration on a flat surface. The gravitational settling of droplets is not included in the model.

$$C_v = \frac{N_s}{2\pi\sigma_y\sigma_z u} exp\left(-\frac{y^2}{2{\sigma_y}^2}\right)\left[exp\left\{-\frac{(z-h)^2}{2{\sigma_z}^2}\right\} + exp\left\{-\frac{(z+h)^2}{2{\sigma_z}^2}\right\}\right] \quad (19)$$

The origin of the coordinates is on the ground just below the emission point. The coordinate axes are the x-axis in the downwind direction, the y-axis at right angles to the x-axis in the horizontal plane, and the z-axis in the vertical direction. The parameters are as follows:

C_v: The number concentration of the virus (m^{-3})

N_s: The number of viruses released per second (s^{-1})

u: The wind speed ($m\ s^{-1}$)

h: The release height = 1.5 m

x,y,z: The coordinates of the receptor points

The plume central axis coordinates are y = 0 m and z = 1.5 m.

σ_y, σ_z: The standard deviation of the distribution C_v in the y and z directions, including dispersion due to atmospheric turbulence and initial dispersion in the environment of the human body (see Equations (21) and (22)).

σ_{ya}, σ_{za}: The standard deviation of the distribution C_v in the y and z directions due to atmospheric turbulence (see Supplementary material 2).

The presence of a human body affects the dispersion at a short distance of less than 3 m. The width of the region of this effect is set to 0.5 m in the vertical and horizontal directions in the vicinity of the human body, based on the human shoulder width. In addition, it is assumed that the plume spreads in this region [4], and the following values are used as the initial dispersion parameters (horizontal σ_{y0}, vertical σ_{z0}).

$$\sigma_{y0} = 0.25 \text{ m}, \ \sigma_{z0} = 0.25 \text{ m} \quad (20)$$

σ_y and σ_z are calculated using the following equations for the dispersion due to atmospheric turbulence and the initial dispersion in the wake of the human body:

$$\sigma_y = \left({\sigma_{ya}}^2 + {\sigma_{yo}}^2\right)^{1/2} \quad (21)$$

$$\sigma_z = ({\sigma_{za}}^2 + {\sigma_{z0}}^2)^{1/2} \quad (22)$$

In the Gaussian plume model, the effect of mechanical turbulence generated by the building is included in the dispersion parameters. Here, the dispersion parameters of three types of dispersion models: EPA-HIWAY-2 [35], the OML model (ground

roughness z_0 = 1 m) [36] and the OMG volume-source model (OMG model) [37, 38] are used. The OMG model uses the diffusion coefficients K_y (m^2s^{-1}) and K_z (m^2s^{-1}) (see Supplementary material 2).

The height at which the virus is released from a human is assumed to be h = 1.5 m above the ground, the receptor height is z = 1.5 m, and the concentration on the central axis of the plume is calculated. The downwind distance x of the dispersion is set to 2 to 100 m from the release point.

The input wind speed is an average wind speed of U_s = 1 m s^{-1} at a height of 1.5 m above the ground in the city. This value is estimated from the annual average wind speed U_a = 2.9 m s^{-1} observed at the airport (Osaka Itami Airport) at a height of 10 m above the ground [39]. The ratio U_s / U_a = 0.34 is estimated using the OSPM [40] of the automobile exhaust gas diffusion model. The ratio is the value obtained when winds blow parallel to a street.

The OMG model is also used to calculate the concentration at U_s = 0.5 m s^{-1} in weak winds. The atmospheric stability is assumed to be neutral because mechanical turbulence predominates near the ground.

4.2 Calculated result

Figure 3 shows the calculated number of viruses inhaled indoors during an hour of conversation. The number of inhaled viruses in the room N_{in} is 14 h^{-1} if the viral load in the infected person's expiratory droplets is 10^8 mL^{-1} and the ventilation volume per person is 30 m^3h^{-1}. The ventilation volume corresponds to an indoor CO_2 concentration of 1000 ppm, which is the Japanese ventilation standard [33]. If the viral load in the infected person's expiratory droplets is 10^{10} mL^{-1} (a super-spreader), N_{in} is 1400 h^{-1}. For a super-spreader, the infection threshold is exceeded even if the ventilation rate is considerably increased. In Fig. 3, there is a difference of 62 times between the maximum and minimum ventilation volume, but the number of inhaled viruses is only 2.4 times. The reason is that for large particles having an initial particle size of 30 µm to 100 µm, the removal rate by gravity is higher than the removal rate by ventilation.

For details, refer to Appendix Table 1 and Supplementary material 3–1 and 3–2. (The calculation process of Figure 3, Supplementary material 3–1 and 3–2 are shown in the sheets “Indoor diffusion calculation–1” and “Indoor diffusion calculation–2” in Supplementary material 4.)

Figure 4 shows the calculated result for the number of viruses inhaled outdoors in one hour of conversation. At a distance of 2 m, if the viral load in the infected person's expiratory droplets is 10^8 mL^{-1}, the number of viruses inhaled is N_{in} = 20-60 h^{-1}. When

the amount of virus in expiratory droplets is 10^{10} mL^{-1} for a super-spreader, the number of viruses inhaled is N_{in} = 2000-6000 h^{-1}. Please note that the concentration is calculated here from droplets with d < 100 μm, and larger droplets are not added to the calculation because they fall to the ground faster. The average wind speed at a height of 1.5 m is 1 m s^{-1}, and the representative wind speed for weak winds is 0.5 m s^{-1}. The concentration for the weak wind is not so different from the concentration at a wind speed of 1 m s^{-1}. The reason for this is that when the wind speed u is 1 m s^{-1} or less, the horizontal wind speed fluctuations σ_u and σ_v (ms^{-1}) are almost constant, and as a result, the horizontal diffusivity (~ σ_v / u) increases [37].

4.3 Discussion

In this study, to investigate droplet nuclear infections, diffusion models were used to calculate the number concentration of SARS-CoV-2 in exhaled droplets during conversation in indoor and outdoor settings and to calculate the number of viruses inhaled by breathing. The release rate of SARS-CoV-2 in expiratory droplets has thus far been unknown due to large fluctuations in measured data. Measurement data from published papers on the diameters and masses of droplets emitted during conversation were analysed to obtain a reliable mean for the prediction. The 95% confidence interval for the population mean of the released expiratory droplet mass in droplets of size 100 μm or less falls within a relatively small variation of 0.5 to 1.5 times the sample mean.

Recently, Pöhlker et al. [42] performed a statistical analysis of published results on the volume distribution of expiratory droplets by particle size. The number of expiratory droplet data sets during talking used for their analysis is five. Three of them, Loudon and Roberts [6], Chao et al. [23] and Xie et al. [8] were used in the analysis in this paper. The others are Duguid [7] and Johnson et al. [22]. The data used by Pöhlker et al. vary by two order of magnitude depending on the experimenter. Pöhlker et al. used a superposition model of multiple lognormal distribution curves (Johnson et al. [22]) for the droplet volume size distribution. In the model, the experimental curve that fits best to the five data is obtained in volume size distribution for speaking [42]. The data of Duguid [7] and Johnson et al. [22] are rather small values (about 5 % of this study for d < 100 μm) and were not used in the analysis in this paper. (See Table 1 and Supplementary material 4 for details.)

Instead, the data used here were those that seemed relatively reliable, and the mean value and standard deviation of the emission amounts were calculated. However, the calculated volume of expiratory droplets with a particle size d<100 μm of Pöhlker et al. is five times the value in this study, and it is the same order of magnitude as this study.

It is interesting that Pöhlker et al. use some different data from this study and calculate in different ways, resulting in the same order of magnitude.

(For more details, please refer to the sheet "Comparison of Pölker model and Kono model" in Supplementary Material 4.)

The solid impaction measurement (droplet deposition analysis, DDA) is used in this study. The problem with the accuracy of the solid impaction measurement method (DDA) is that small droplets and nuclei that are suspended in the box for a long time are not measured. Droplets evaporate to reduce their size, and as a result, they are suspended in the box. The evaporation rate is affected by the relative humidity and temperature. Of the four sets of DDA data, Xie et al. and Johnson et al. measured the relative humidity and temperature [42]. It would be useful to use DDA to capture changes in the number of particles deposited on the floor surface with changes in the humidity and temperature. Furthermore, it is necessary to improve the accuracy of experimental data on the number of expiratory droplets released and increase the amount of experimental data.

Next, the fluctuation range of the data on the prediction of the number of viruses inhaled is described. The number of viruses in expiratory droplets is a factor of 100 different between 10^8 mL^{-1} and 10^{10} mL^{-1}. In this research, the individual difference in expiratory droplets is up to 3 times the mean value, with the coefficient of variation being 1 (see the data of Xie in Table 1). The change in concentration due to humidity in the room is doubled between the cut-off droplet sizes are 100 μm and 70 μm. Outdoors, the concentration at the cut-off diameter of 130 μm is three times the concentration at 100 μm. Therefore, among the variations in the data handled here, the number of viruses in expiratory droplets has the greatest effect on the calculated results.

The minimum number of SARS-CoV-2 infectious viruses is estimated to be of the order of hundreds from a modelling and microbiological point of view. However, the overall quality of the evidence is low [16]. Since it is not possible to carry out experiments using humans for SARS-CoV-2, studies to estimate the minimum number of infectious viruses coming from indoor infection cases by back calculation from the number of infected people, room ventilation rate, and virus exposure doses have been conducted by Watanabe et al. [41], Prentiss et al. [14], and others. It is expected that this study will provide more accurate forecast data for the dose-response model.

The droplet emission data used for predictions so far will be compared with the data from this study. For example, regarding the probability of infection in a room, Oliveira et al. [5] assume SARS-CoV-2 initial viral loads of $N_0 = 10^8$–10^{10} copies mL^{-1} are released during 1 hour of conversation. The probability of infection is estimated to

be 0.1–11% for once-hourly ventilation. Here, the infection probability is calculated using the 10% infection probability (20–83 PFU) and 50% infection probability (= 130–530 PFU) [41] of SARS-CoV-1. However, droplet mass release during exhalation is underestimated by about 5 % compared to this study due to the use of data from Johnson et al. [22].

In addition, Prentiss et al. [14] used data from five infections in China, South Korea and the United States that occurred between January and March 2020 to estimate the minimum number of SARS-CoV-2 viruses N_t that caused the infections. They used an exponential model. As a result, N_t is found to be 300–2000. The mass of droplets released in conversation gives $S = 7.6 \times 10^{-3}$ mg s^{-1}, which is about 10 times the value of S obtained in this paper, which is too large. Prentiss et al. calculated the number of droplets from a laser sheet of water droplets emitted during conversation [43]. The total volume of water droplets was calculated by multiplying the mean value of the volume of the smallest particle (12 μm in diameter) and the volume of the largest particle (21 μm in diameter) by the total number of water droplets. It is assumed that this is a 10-fold excessive value because the approximate value is used without taking the droplet size distribution into account. (Note that the viral load in expiratory droplets is given as $N_0 = 10^7$ copies mL^{-1}, which is 1/10 of the viral load given in this paper. Therefore, the viral release rate is the same as in this paper.)

Calculations show that the calculated number of inhaled viruses in the room, N_{in} (h^{-1}), is 1400 when the amount of virus released by the infected person is $N_0 = 10^{10}$ mL^{-1} and the per capita ventilation rate is 30 m^3 h^{-1}. The ventilation rate corresponds to the Japanese ventilation standard of CO_2 concentration 1000 ppm [33]. The above value exceeds the infection threshold number, which is several hundred. Even if the CO_2 concentration is 500 ppm and the ventilation rate is strong, with replacement with the outside air occurring every 8 minutes, the number of inhaled viruses is still within the error bar of the infection threshold.

When the viral load in expiratory droplets is 10^8 mL^{-1} or less, the result is below the infection threshold even with Japan's current ventilation standards with a CO_2 concentration of 1000 ppm or less.

In this work, a single box model was used, and it is assumed that the virus number concentration in the room is uniform. However, recently, a short-range diffusion model [44] was used to predict the virus number concentration distribution within 3 m of a virus releaser and was combined with the average virus number concentration in the room to calculate the necessary ventilation [45]. However, even if the resolution of the diffusion model is increased, it cannot be balanced because the accuracy of the

conventional expiratory droplet emission data is low.

In order to predict the virus number concentration distribution with higher accuracy, it is necessary to improve the data accuracy of the number of expiratory droplets released.

5. Conclusion

The release rate of SARS-CoV-2 in expiratory droplets has so far been unclear due to large variations in measured data. Here the measurement data from published papers on the diameters and masses of expiratory droplets during conversation have been analysed to obtain a reliable mean for the calculation. The 95% confidence interval for the population mean of the mean release mass for droplets of size 100 μm or less falls within a relatively small variation of 1/2 to 1.5 times the sample mean.

In order to investigate droplet nuclei infection, a diffusion model was used to calculate the number concentration of SARS-CoV-2 in expiratory droplets during conversation indoors and outdoors. The virus number concentration and the inhaled virus number were calculated for one infected person speaking for one hour in a room. The amount of virus used in the calculation was in the upper 10% of values for all infected persons, 10^8 mL^{-1} [13], or the top 2%, 10^{10} mL^{-1} (for a super-spreader). The result was that the occurrence of infection in the room largely depends on the amount of virus contained in the expiratory droplets. If the viral load is 10^8 mL^{-1}, the virus number concentration can be kept below the infection threshold using ventilation. When the viral load is 10^{10} mL^{-1}, the virus number concentration is within the error bar of the infection threshold even if the ventilation rate is increased to produce a CO_2 concentration of 500 ppm. In this case, most of the people in the room will be infected. Therefore, it is important to identify super-spreaders, as well as to wear masks when speaking indoors and to increase ventilation rates.

In addition, the diffusion model was used to predict the average hourly virus number concentration outdoors. Here, it is assumed that one infected person keeps talking. The result was that when the viral load in the expiratory droplets is 10^8 mL^{-1}, the distance to reach the infection threshold in one hour of conversation is less than 1 m, and when the distance is 2 m or more, the number of inhaled viruses is below the infection threshold. However, in the case of a super-spreader with a viral load of 10^{10} mL^{-1}, the infection threshold is exceeded at a distance of 2 m. Therefore, a mask is advisable when speaking outdoors. However, in the absence of conversation, a mask is usually not required except in crowded areas.

These predictions are consistent with previously reported infection data that

transmission occurs indoors and are rare outdoors.

The number of reliable data measuring the total amount of expiratory droplets during talking is extremely small. In order to improve the accuracy of predicting the concentration of virus numbers, it is necessary to improve the experimental method to measure the number of expiratory droplets, and increase the number of experimental data.

Supplementary material 4: The calculation process and the data used for the analysis and are shown in the supplementary material 4.

Competing interests

I declare I have no competing interests.

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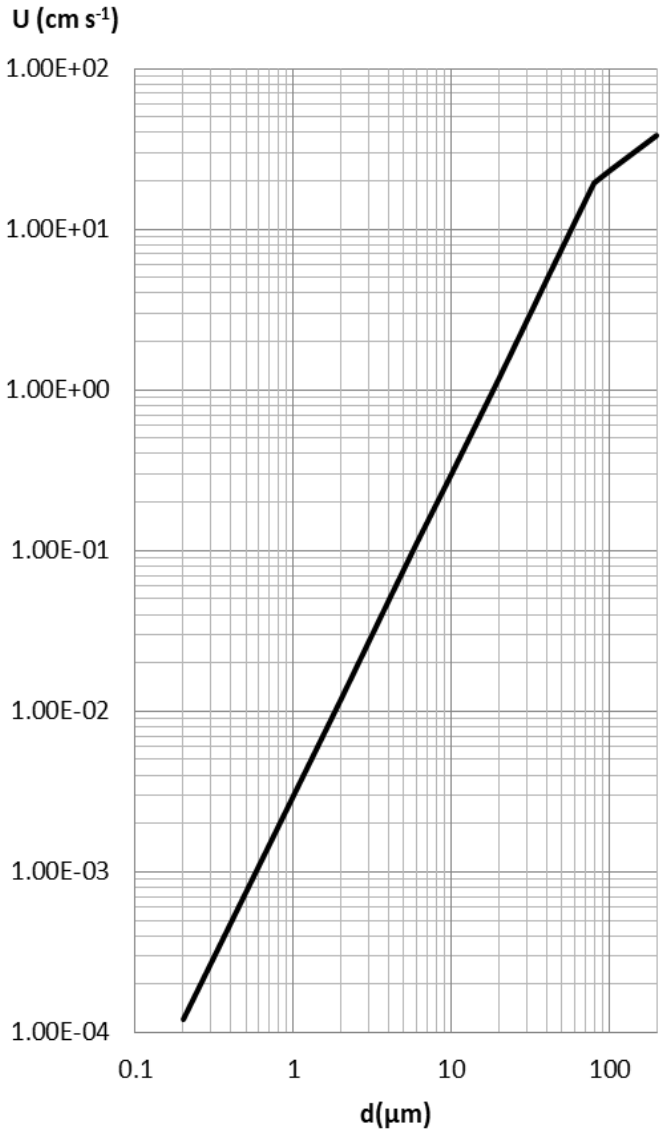

Fig. 1 Terminal velocity of a droplet, U (cm s^{-1}).
The density of the droplet is ρ = 1000 (kg m^{-3}).
The shape of the droplet was assumed to be a sphere. d : diameter (µm).

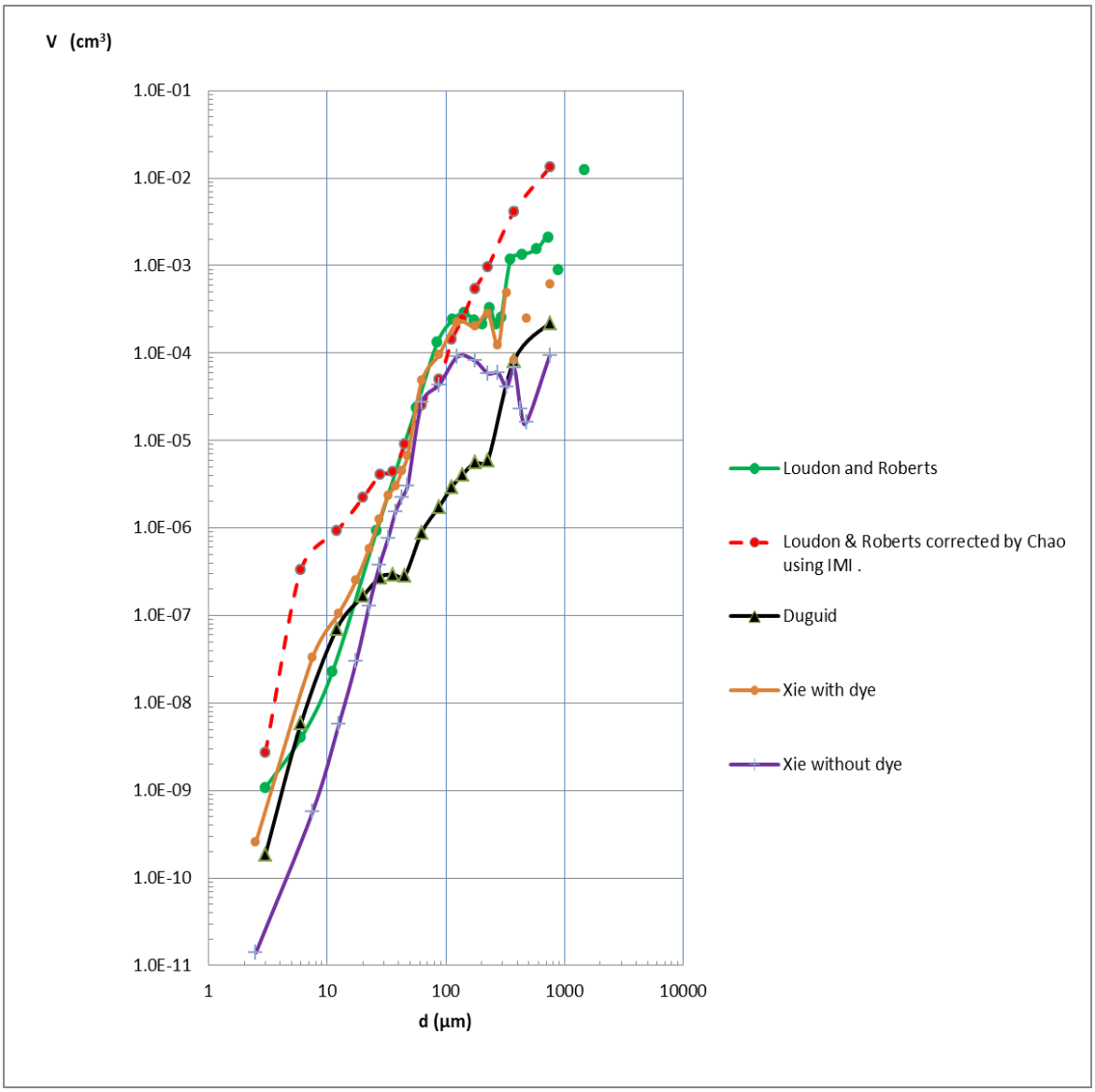

Figure 2 Cumulative volume distribution by size of droplets released during talking.
Loudon and Roberts (L & R), L & R corrected by Chao using IMI, Duguid,Xie (with dye), Xie(without dye)

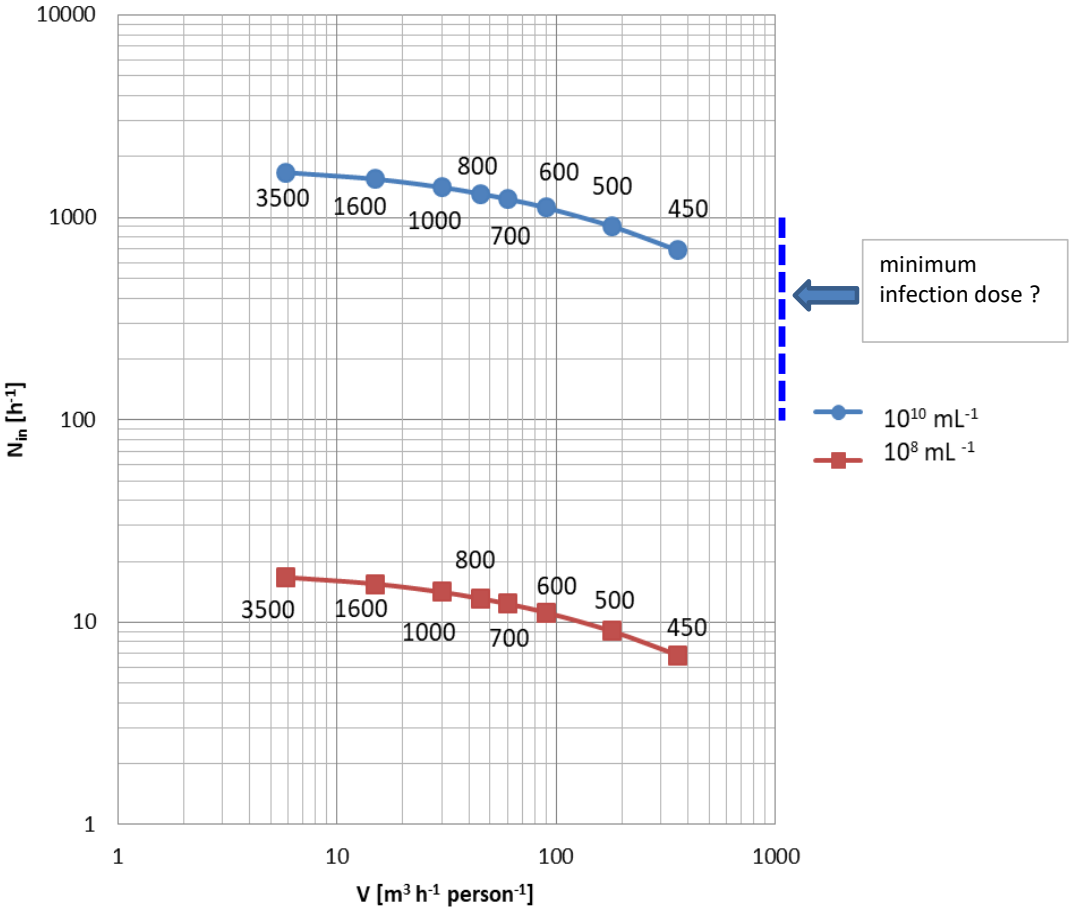

Figure 3 Calculated number of viruses inhaled through the nose and mouth for 1hour in a room and estimated range of minimum infection dose. [16]
Outside air CO_2 = 400 ppm

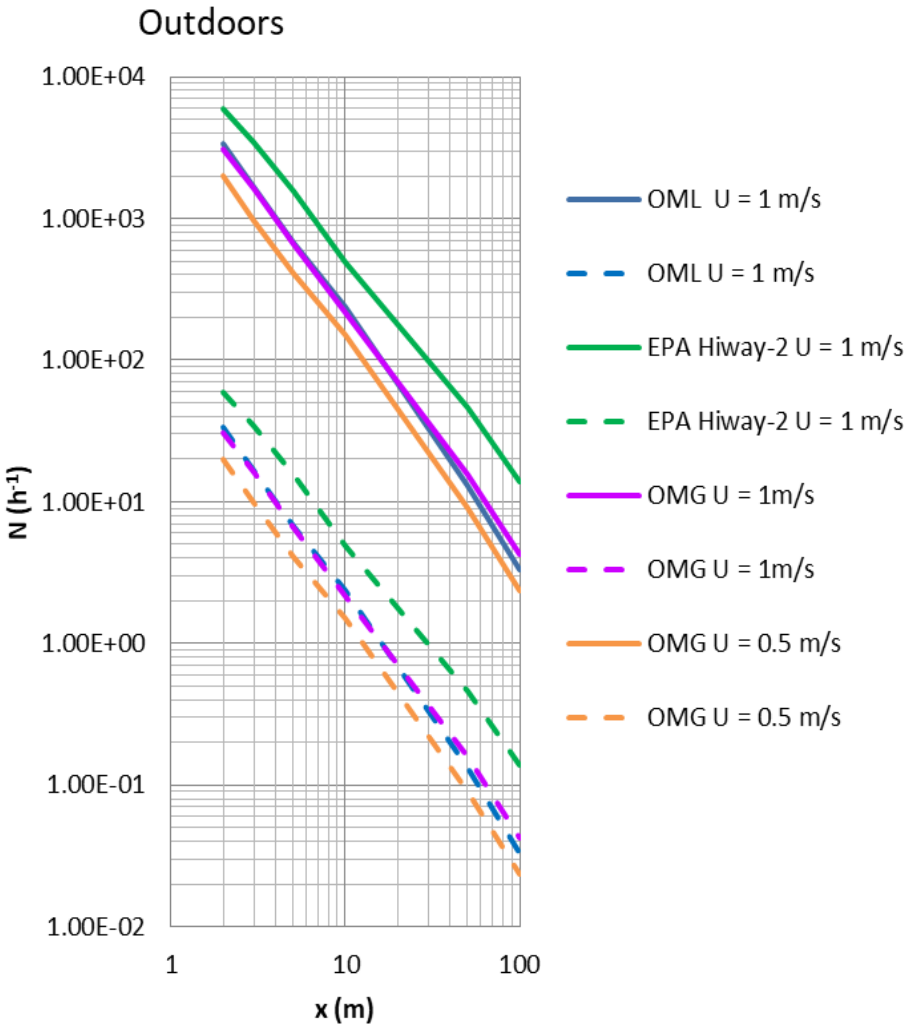

Figure 4 Calculated number of viruses inhaled through the nose and mouth for 1hour in outdoors.
x is the downwind distance between the virus emitter and the person who inhales the virus.
solid line: 10^{10} copies mL^{-1}, broken line 10^{8} copies mL^{-1}.

Table 1 Mass of exhaled droplets by droplet size during talking loudly counting from 1 to 100 in 100 seconds. (mg / 100 seconds)

	author	methods	Statistical parameters	total mass	diameter 2～150 μm	diameter 2～130 μm	diameter 2～100 μm	diameter 2～75 μm	ratio <150μm to <100μm	ratio <130μm to <100μm	ratio <75μm to <100μm	sample size n
(1)	**L and R [6]**	**solid impaction**	**mean**	**21.4**	**0.69**	**0.40**	**0.159**	**0.025**	4.3	2.5	0.15	6
			σ_{n-1}	6.4	0.25	0.131	0.042	0.0081	-	-	-	
			C.V.(%)	30	36	33	27	33	-	-	-	
(1a)	**correction the data in (1) to the data without dye**		**mean**	**5.1**	**0.30**	**0.176**	**0.076**	**0.0128**	4.0	2.3	0.17	6
(1b)	**L & R-IMI [23]**	**corrected by IMI**	**mean**	**19.4**	**0.48**	**0.24**	**0.096**	**0.047**	5.0	2.5	0.49	6
(1c)	**correction the data in (1b) to the data without dye**		**mean**	**4.7**	**0.21**	**0.105**	**0.046**	**0.024**	4.6	2.3	0.53	6
(2)	**Duguid [7]**	**solid impaction**	mean	0.33	0.0108	0.0067	0.0037	0.00199	2.9	1.8	0.53	10-22
(3)	**Xie [8]**	**solid impaction without**	**mean**	**0.61**	**0.170**	**-**	**0.079**	**0.035**	2.2	-	0.45	7
			σ_{n-1}	0.64	0.187	-	0.099	0.051	-	-	-	
			C.V.(%)	104	110	-	126	146	-	-	-	
(4)		**solid impaction with dye**	**mean**	**2.44**	**0.39**	**-**	**0.163**	**0.067**	2.4	-	0.41	5
			σ_{n-1}	1.44	0.171	-	0.081	0.046	-	-	-	
			C.V.(%)	59	44	-	49	68	-	-	-	
(5)		**mask**	**mean**	**18.7**	-	**-**	-	-	-	-	-	8
			σ_{n-1}	21.5	-	-	-	-	-	-	-	
			C.V.(%)	115	-	-	-	-	-	-	-	
(1a)+(3) mean (*) (**)			**mean**	**-**	**0.23 (1)***	**-**	**0.078 (1)***	**0.035****	2.9	-	0.45**	13
		95% confidence interval of the polulation mean (ratio)			**0.14～0.33 (0.59～1.4)**	**-**	**0.036～0.12 (0.47～1.5)**	**-**	**-**	**-**	-	
			σ_{n-1}	-	0.158	-	0.069	-	-	-	-	
(1)+(4)			**mean**	-	**0.55 (1)**	**-**	**0.161 (1)**	**0.044 (1)**	3.4	-	-	11
		95 % confidence interval of the polulation mean (ratio)			0.38～0.72 (0.69～1.31)	-	0.12～0.20 (0.76～1.24)	0.019～0.068 (0.44～1.56)	-	-	-	
			σ_{n-1}	-	0.26	-	0.059	0.037	-	-	-	

The data of Xie et al (table 2)[8] does not divide the size range by 130 μm and is 100-150 μm, so 130 μm or less is not calculated.

* average of (1a) and (3).

** Geometric mean of mass ratio of 75 μm or less to 100 μm or less of (1b), (3) and (4).

σ_{n-1}: standard deviation, C.V.: coefficient of variation

The method for estimating the average of mass with a diameter of 75 μm or less is different from the method for obtaining that with a diameter of 100 μm or less. Since the mass of 75 μm or less of L & R (in Table 1) are small compared to the values of other researchers, this value cannot be used. Instead, the mass ratio of L & R-IMI and Xie of 75 μm or less and the mass ratio of 100 μm or less are close to each other, so the average mass ratio of them was calculated. From this average mass ratio and the previously obtained average mass of 100 μm or less(0.078mg/100s), an average mass of 75 μm or less, (0.035 mg /100 s) was obtained. (Assuming that this mass ratio does not change with and without food dye, the mass ratio of the data of Xie's with food dye is also included.)

Appendix-Table 1 Calculation of droplet mass contributing to the number of inhaled viruses per hour indoors. The mass of the droplet is the L & R data corrected using IMI. [23]

initial diameter d_0 (µm)	final diameter d_f (µm) RH = 0 - 0.6	evaporation time (s) **	terminal velocity vt (m s^{-1}) final diameter	gravitational setting time τ =1.5/ vt (s)	time ratio to 1 hour (TR)	d_0 range (µm)	rerease rate of initial droplet mass (mg s^{-1})
100	27	15-20	* 0.022	69	0.019	75-100	4.9E-04
70	19	10	0.0107	140	0.039	50-75	2.6E-04
50	14	5	0.0055	275	0.076	40-50	9.1E-05
40	11	3.3	0.0035	430	0.12	32-40	4.4E-05
30	8.1	1.6	0.0020	760	0.21	24-32	4.1E-05
20	5.4	0.7	0.00088	1720	0.48	16-24	2.2E-05
12	3.2	0.2	0.00032	4800	1	8-16	9.2E-06
6	1.6	0.1	0.000079	19000	1	< 8	3.4E-06
						total	9.6E-04

* initial diameter

** Olibeira [5] Fig. 7a (low protein, RH = 0.6)

Appendix Table 2 Measurement methods, principle and range of droplet sizes and numbers.

meathods	principle	measurement range (resolving power)	total mass measurement	reference
solid impaction (slips of celluloid-surfaced slide / dye)	microscope	> 10～20μm (> 1 μm)	yes	Duguid [7]
solid impaction (slips of paper / dye)			yes	Loudon and Roberts [6]
solid impaction (microscope glass slides and slips of water-sensitive pape / with dye and without dye)			yes	Xie et al. [8]
surgical face mask and plastic bag	analytical balance (Shimadzu AUW 220)	accuracy of 0.1 mg	Yes	Xie et al.[8]
laser aerosol spectrometer (Grimm 1.108, Germany) [24][25]	Laser light scattering, I = f(d)	0.3 ～ 20 μm	no	Xie et al. [8]
IMI, Inerferometric Mie imaging [26]	interference between the light reflected by the droplet surface and the light refracted after passing through the droplet	2 ～2000 μm	Estimation	Chao et al. [23]
a laser particle size analyser, Spraytec system (Malvern instruments Ltd. UK)	Laser diffraction	0.1～1000 μm	no	Han et al. [21]
APS, Aerodynamic particle sizer, (APS model 3321) [27]	observe velocity, hydrodynamic method, time-of-flight	0.5 ～20μm	no	Johnson et al. [22]

, * solid impaction measurement method = droplet deposition analysis, DDA

Appendix Table 3 Relationship between CO_2 concentration, room ventilation rate (V), and ventilation time (T).
T (minutes) is the time when the air in the room is replaced with the outside air by ventilation.

room CO_2(ppm)	room CO_2-outside CO_2 (ppm)	V ($m^3 person^{-1} h^{-1}$)	T(min)
450	50	360	4
500	100	180	8
600	200	90	16
700	300	60	23
800	400	45	31
1000	600	30	47
1600	1200	15	93
3500	3100	5.8	241

outside CO_2 = 400 ppm room volume: 700m^3, 30persons
Office work