Droplet Concentration Produced during Expiratory Activities and Evaluation of Relative Infection Risk

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Abstract. The outbreaks caused by COVID-19 have prompted researchers to quantitatively assess the risk of infection. Since airborne transmission is caused by inhalation of droplet from infected persons, it is important to understand the droplet concentration and size distribution of aerosols. In this study, we examined the size distribution of droplets produced by various expiratory activities, compared the results with previous studies, and tested the consistency of a simple measurement method. We realized the measurement by conducting the experiment in a clean room with low background concentration, using an optical particle counter and a device that can constantly ventilate the generated droplets. Quanta emission rate is a method of evaluation the risk of infection. Among the variables in the equation to determine it, we measure droplet concentration and inhalation rate, which we can measure, and from the product we get the relative risk of infection for each of the various expiratory activities. In the expiratory activities, in addition to the same cases as in the previous study, we conducted conversations and vocalizations while wearing a mask. In this study, we mainly analysed particles smaller than 1μm, based on the theory that viruses are highly proliferative and pose a high risk of infection. The concentration of droplets generated by exhalation activity is dominated by particles smaller than 1 μm in number concentration, but only a small percentage in mass concentration. In addition, the risk of infection increased in proportion to the volume of voice, and loud vocalizations showed a prominent risk of infection. Furthermore, it was confirmed that the risk of infection was reduced by wearing a mask, and the degree of reduction depended on the method of wearing the mask.

Keywords. Evaluation of SARS-CoV-2 (COVID-19), Expiratory-aerosol, Particle size distribution of droplets, Coronavirus, Masks effect
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1. Introduction

In order to evaluate the risk of infection via aerosols, it is important to understand the droplets concentration and the size distribution of aerosols in infected individuals. Therefore, we first examined the particle size distribution of droplets produced by various expiratory activities. Buonanno proposed the quanta emission rate, expressed in equation (1), as a method to evaluate the risk of contagion [1].

$$ER_q = c_v \cdot c_i \cdot IR \cdot V_d \qquad (1)$$

Where c_v is the viral load in the sputum (RNA copies mL^{-1}), c_i is the amount of virus expressed in terms of viral RNA copies corresponding to 1 quanta (quanta RNA $copies^{-1}$), IR is the inhalation rate ($m^3\ h^{-1}$), V_d is the droplet volume concentration ($mL\ m^{-3}$). In this study, we measure IR and V_d, which we can measure, and use the product ($IR \cdot V_d$) to evaluate the relative risk of infection for various vocalization patterns and when wearing a mask.

2. Experimental methods

2.1 the droplet measurement methods

To achieve the objective, a low background environment was required, so we conducted our experiments in an ISO standard class 5 clean room. The measurement of droplet due to expiratory

activities is done by Morawska [2] using a small wind tunnel in which the subject can put their head and in which a built-in HEPA filter provides a clean environment. In this experiment, a zinc-based duct with a ventilation fan was installed in the clean room to enable simple measurements. **Fig. 1** shows the measurement device. By ventilating the air in the duct with a fan attached to the duct at 48.5 m^3h^{-1}, it was assumed that the droplet concentration in the duct is uniform a few seconds after the utterance. To confirm that the air in the duct was in a steady state, we measured the CO_2 concentration, which indicated that 80~90% of the air was in a steady state at the position where the particle counter was measured. An optical particle counter is installed inside the duct to measure the steady-state concentration in the duct. The inlet of the particle counter is placed at 15 cm from the mouth. The air mixed with the droplets sucked in by the fan is exhausted outside the room. **Tab. 1** shows a comparison of measurement methods with Morawska.

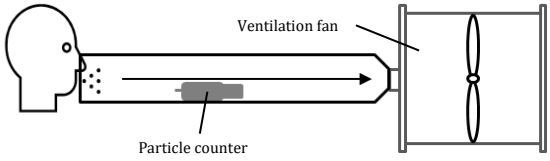


Fig. 1 - Measurement device.

2.2 measurement protocol

This study was conducted by five subjects, two males and three females. In order to match the volume of the voice of each subject, the measurement was performed while constantly checking the value of the sound level meter placed right next to the face. The vocalizations were performed for 2 minutes, and the activity intervals were defined for each expiratory activities and measured using a metronome to avoid differences in the number of vocalizations between subjects.

Three major types of expiratory activities are performed and are shown in **Tab. 2**. The details of each activity are described below.

1. Comparison with previous studies

We performed expiratory activities like those performed in Morawska's study to examine the accuracy of a simple measurement method.

・Nasal breathing:
Breathe in through the nose and out through the nose.
・Breathing:
Breathe in through the nose and out through the mouth.
・Whispered:
Counting in Japanese for 10 s at a whisper.
・Voiced:
Counting in Japanese for 10 s at normal voice.
・Unmodulated:
Unmodulated vocalization with “aah”.

2. Vocalization for conversation

The Japanese greeting *“ohayougozaimasu”* was uttered at three levels of voice volume.

3. Vocalizing while wearing a mask

A total of six cases of nasal breathing, mouth breathing, and normal voice greetings were performed, with the mask firmly in place and with only the nose out. The masks were made of non-woven fabric with a VFE test of 99%, and all the subjects used the same size.

Tab. 2 – Type of expiratory activities, its volume, and how the mask is worn.

	Activity	Volume	3. Mask
1.	Nasal breathing	—	—
			Nose out
			Cover all
	Breathing	—	—
			Nose out
			Cover all
	Whispered	40dB	—
	Voiced	60dB	—
	Unmodulated	90dB	—
2.	Vocalization for conversation	40dB	—
			—
		60dB	Nose out
			Cover all
		90dB	—

Tab. 1 – Comparison of measurement methods with Morawska.

	This study	Morawska[2]
Instrument and Particle size	Particle counter (KANOMAX model 3889) The instrument has a minimum measurement interval of 6 s and measure s the particles in the diameter range 0.3-0.5 μm, 0.5-1.0 μm, 1.0-3.0 μm, 3.0-5.0 μm, 5.0-10.0 μm, 10.0 μm ≤. Details of the four particle sizes shown in the results : 0.3-1.0 μm, 1.0-3.0 μm, 3.0-5.0 μm, 5.0-10.0 μm	Particle sizer (APS TSI model 3312A) The instrument measures the particles in the diameter range 0.5-20.0 μm and detects particles as small as 0.3 μm. Details of the four particle sizes shown in the results : ≥0.8±0.08 μm, 1.8±0.3 μm, 3.5±0.7 μm, 5.5±1 μm
Vocalization method	・Breathe in through the nose and out through the mouth (Breathe for 3.24 s per set for 2 min) ・Counting in Japanese for 10 s (Count from 1 to 10 in 3.75 s per set for 20 sets) ・Unmodulated (Vocalize “aah” for 3 s per set for 20 sets) Since the instrument reports the sum of 6 s, the duration of the vocalizations was determined by metronome rhythm, which can be performed in 6 s or less. When the subjects finished voiced, they held their breath until the next 6 s measurement began, and then took 20 6 s measurements, for a total of 2 min.	・Breathe in through the nose and out through the mouth (Breathe at a natural pace for 2 min) ・Counting in English for 10 s (Alternate 10 s of counting and 10 s of natural breathing for 2 min) ・Unmodulated (Alternate 10 s of vocalization “aah” and 10 s of natural breathing for 2 min) The subjects were given a demonstration on how to vocalize, and the timing of the activity was determined by looking at the second hand on an analog clock.
Calculation method	To compare with previous studies, the values obtained in this experiment were converted using the following equation. Droplet number concectration per vocalization = Measured number concentration × $\frac{T_i}{T_v} \times \frac{Q_f}{IR}$ T_i : Minimum measurement interval of the instrument T_v : Vocalization time for each case Q_f : Airflow rate of ventilation fan(m^3h^{-1}) IR : Inhalation rate(m^3h^{-1})	The number concentration was obtained by multiplying the dilution factor (D) calculated from the following two equations to indicate the concentration in the upper respiratory during expiration (1) $D = \frac{AH_0}{AH_s - AH_{BG}}$ (2) $AH = \frac{RH}{100} \frac{P_{sat} MW_{H2o}}{RT}$ AH_0 : the water vapor concentration in the respiratory tract AH_s : the water vapor concentration in the sample AH_{BG} : the background air water vapor concentration RH : relative humidity(%) P_{sat} : the saturation vapour pressure of water at T MW_{H2o} : the molecular weight of water R : the gas constant T : the temperature(K)
Background number concentration	Measurements without a subject : $3 \times 10^{-3}(cm^{-3})$ Measurement in the presence of a subject : $7 \times 10^{-3}(cm^{-3})$	Background concentrations were measured by adjusting the airflow in the wind tunnel so that the subject's breath was directed away from the probe. Measurements without a subject : $5 \times 10^{-4}(cm^{-3})$ Measurement in the presence of a subject 10 cm from the subject's face : $1.5 \times 10^{-3}(cm^{-3})$ Right in front of the subject's eyes : $6 \times 10^{-3}(cm^{-3})$

In this experiment, the subjects had to prove negative by PCR test beforehand to avoid infection.

2.3 the inhalation rate measurement methods

We used the Aero monitor AE-3105 to measure the inhalation rate. The measurement is performed by connecting a transducer with a special mask attached. This device can acquire data every 0.1 s.

2.4 analysis methods

When comparing with previous studies, the values obtained in this experiment were multiplied by the airflow rate of the fan ventilating the duct and divided by the inhalation rate to convert the number concentration per exhalation 1 cm^3.
Santarpia has performed an analysis on the presence of RNA and proliferative potential of the virus for patients with covid19. The presence of RNA was confirmed in all particle sizes, but the statistical superiority of RNA replication was observed in particle sizes less than 1 μm, with a 90~95% confidence level in the 1~4 μm range, and no superior replication above 4.1 μm [3]. Morawska et al. also proposed that the size of droplets depends on where they are produced, with 1 μm in the bronchi, 5 μm in the pharynx, and 50 μm in the oral cavity, and the risk of infection for particles less than 1 μm produced in the bronchi [4]. Based on these theories, we mainly analysed particles smaller than 1 μm in calculating the relative risk of infection.
In order to calculate the relative risk, the volume concentration of droplets was calculated by assuming a spherical shape based on the average diameter of each particle size range, and the mass concentration was calculated by multiplying the volume concentration by the density of water, assuming that droplets are water molecules.
Moreover, all the results were calculated by subtracting the background concentration from the measured concentration, and the background concentration was measured with the face close to the duct and without exhaling, just as during vocalization. When calculating the effect of the mask, the background concentration measured with the mask on was used.

3. Results and discussion

3.1 comparison with previous studies

The measurement results of this study were converted to the number concentration per exhalation 1 cm^3 and compared with previous studies in **Tab. 3**. As a result, the trend of values in this study and the previous studies was generally the same, confirming the reliability of the data of the simple measurement method. The results for 0.8 μm and 1.8 μm in this study are larger than those in the previous study, but the error in the conversion of 1.8 μm is thought to be caused by the difference in classification between the measurement equipment used in the previous study and the equipment used in this study.

Tab. 3 – Comparison of droplet number concentrations (cm^{-3}) with previous studies.

Particle size	0.8μm	1.8μm	3.5μm	5.5μm
Morawska[2]				
Breathing	0.084	0.009	0.003	0.002
Whispered	0.110	0.014	0.004	0.002
Voiced	0.236	0.068	0.007	0.011
Unmodulated	0.751	0.139	0.139	0.059
This study				
Breathing	0.135	0.058	0.000	0.000
Whispered	0.157	0.028	0.003	0.000
Voiced	0.271	0.115	0.003	0.000
Unmodulated	1.183	0.890	0.066	0.018

The results for each subject are shown in **Fig. 2**. This result shows that droplet concentration varies from individual to individual and that some subjects generate more droplets than others. However, the result of Fig. 2 multiplied by *IR* to the number of droplets per hour (**Fig. 3**) shows that the result for another subject is the highest. Subject C has a high droplet concentration and a high inhalation rate, while subject B has a low inhalation rate in relation to the droplet concentration, which is probably the reason for the extremely high value. The inhalation rate would not be negligible since it is the Number concentration per hour that is related to the risk of infection.

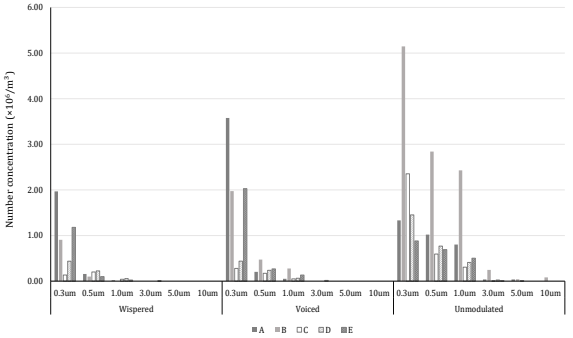


Fig. 2 - Number concentration per exhalation 1 cc for each subject and each particle size.

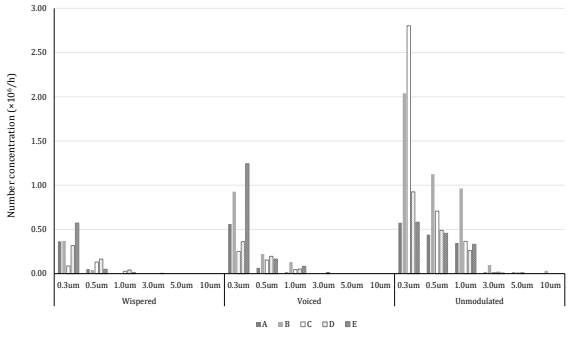


Fig. 3 - Number concentration per hour for each subject and each particle size.

3.2 vocalization for conversation

The sum of the mass concentrations per hour of particles less than 1 μm is shown in **Fig. 4**. From this result, it can be said that the droplet concentration is roughly proportional to the loudness of the voice. Next, **Fig. 5** shows the sum of the mass concentration of particles of all sizes. In this graph, the droplet concentration when speaking at 90 dB is prominent. This result suggests that although there are individual differences, large diameter droplets are generated when the voice is loud, and the generation of large diameter particles has a significant effect on the results when converted in terms of mass concentration.

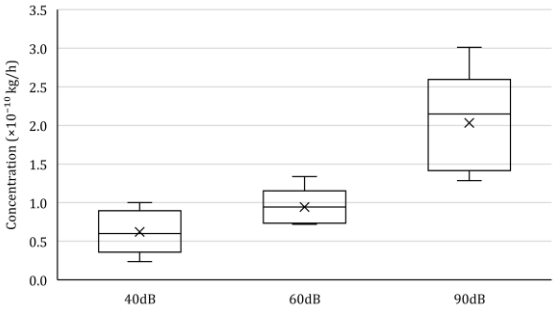


Fig. 4 - Mass concentration of particles less than 1 μm per volume of voice.

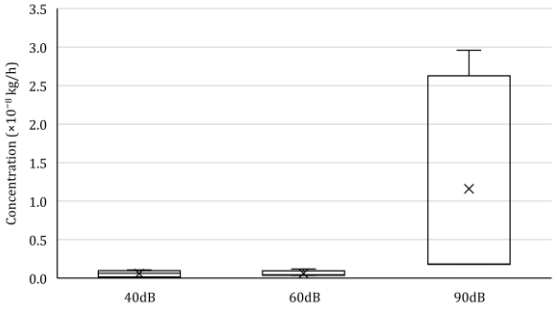


Fig. 5 - Mass concentration of particles of all sizes per volume of voice. Error bars show the standard error of the mean.

The comparison with the previous study in the previous section shows that particles smaller than 1 μm account for most of the total generation in terms of number concentration, while **Fig. 6** shows that their ratio is negligible in terms of mass concentration.

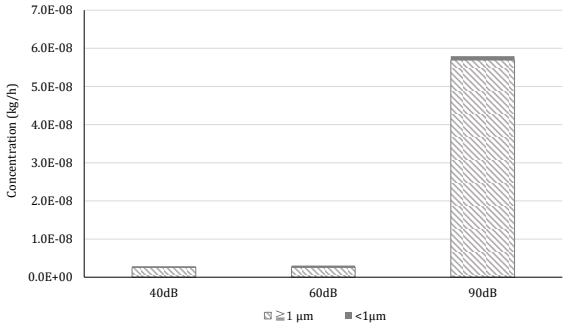


Fig. 6 - Comparison of mass concentrations of particles less than 1 μm and larger particles.

3.3 vocalization while wearing a mask

Fig. 7 shows the droplet generation volume with the mask on divided by the droplet generation volume without the mask on. This shows the extent to which the generated droplets penetrate the mask. Particles with a diameter of 3 μm or more were completely collected by the mask, indicating that the smaller the particle size, the more virus leaked through the mask. In addition, when the mask was worn so that the nose was exposed, the transmission rate increased slightly compared to when it was completely covered.

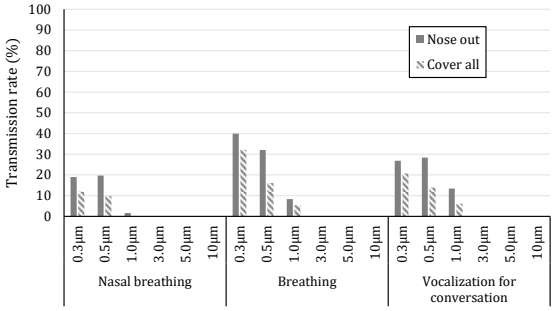


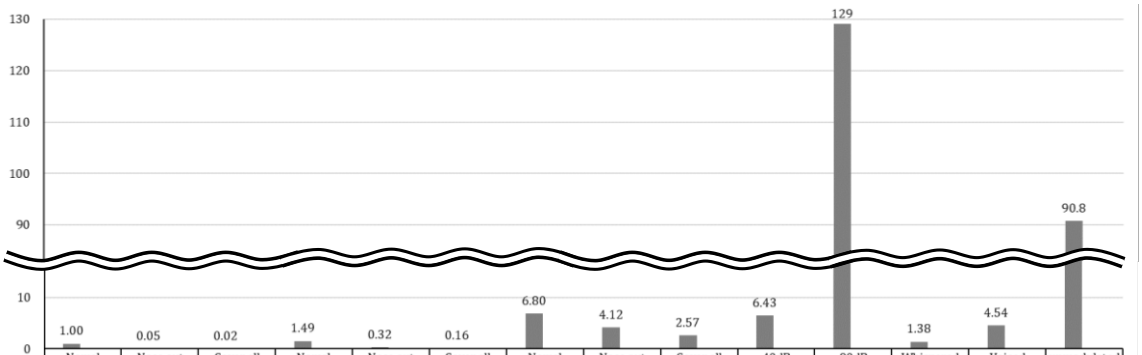
Fig. 7 - Average transmittance of the mask for all subjects, by particle size.

3.4 relative risk from expiratory activities

The average value of $IR \cdot V_d$ for nasal breathing without wearing a mask was set to 1. The results calculated for total particle size are shown in **Fig. 8**, and those calculated for particles less than 1 μm are shown in **Fig. 9**. For particles less than 1 μm, there was no difference in the risk of infection from activity compared to particles of all sizes, but both results showed that vocalization without a mask was several times riskier than breathing, with the risk increasing with the volume of the voice. Furthermore, wearing a mask reduced the risk of infection in all expiratory activities. For particles less than 1 μm, for which infection risk has been proposed, the reduction in infection risk by wearing masks is clear.

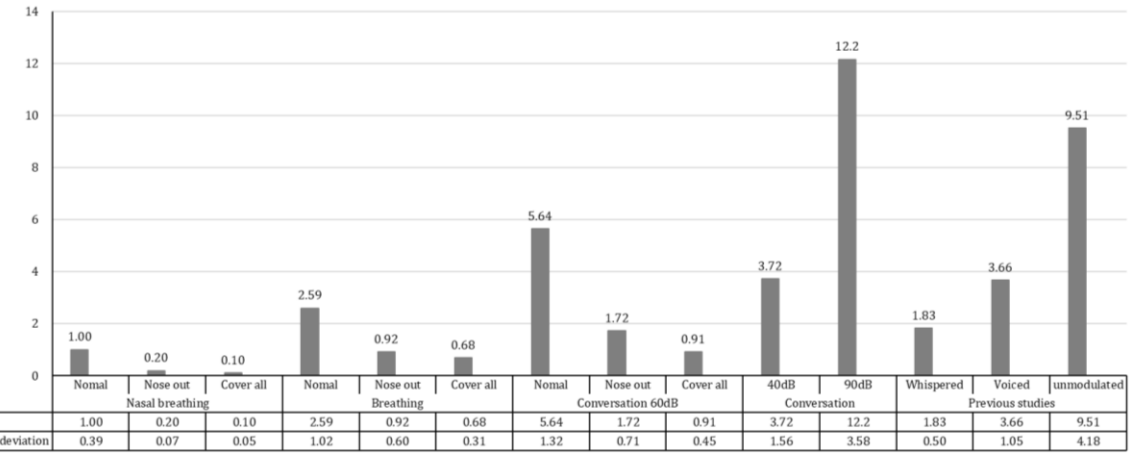
4. Conclusions

The results of this study showed that even a simple method can generally identify trends the droplets concentration and the size distribution of aerosols. The droplet concentration during the expiratory activities varied considerably among the subjects, but in all subjects, particles with a diameter of 1 μm accounted for a large percentage when converted to number concentration, and the percentage was very small when converted to mass concentration. The droplet concentration was proportional to the loudness of the voice for all particle sizes, but the droplet concentration for large particle sizes was much higher when the voice was loud. The smaller the particle size, the more difficult it is for the mask to collect infectious particles, but it was confirmed that the mask reduced the risk of infection for particles less than 1 μm in diameter. Moreover, to further reduce the risk of infection, it is important to wear a mask in the correct way.



	Nomal	Nose out	Cover all	Nomal	Nose out	Cover all	Nomal	Nose out	Cover all	40dB	90dB	Whispered	Voiced	unmodulated
	Nasal breathing			Breathing			Conversation 60dB			Conversation		Previous studies		
Average	1.00	0.05	0.02	1.49	0.32	0.16	6.80	4.12	2.57	6.43	129	1.38	4.54	90.8
Standard deviation	1.02	0.04	0.01	1.20	0.22	0.08	3.53	5.50	3.85	4.19	136	0.78	2.11	110

Fig. 8 - Relative risk of infection for each expiratory activities at all particle sizes, with the mean value of all subjects in $IR \cdot V_d$ for nasal breathing set to 1.



	Nomal	Nose out	Cover all	Nomal	Nose out	Cover all	Nomal	Nose out	Cover all	40dB	90dB	Whispered	Voiced	unmodulated
	Nasal breathing			Breathing			Conversation 60dB			Conversation		Previous studies		
Average	1.00	0.20	0.10	2.59	0.92	0.68	5.64	1.72	0.91	3.72	12.2	1.83	3.66	9.51
Standard deviation	0.39	0.07	0.05	1.02	0.60	0.31	1.32	0.71	0.45	1.56	3.58	0.50	1.05	4.18

Fig. 9 - Relative risk of infection for each expiratory activities at particle sizes less than 1 μm with the mean value of all subjects in $IR \cdot V_d$ for nasal breathing set to 1.

5. Acknowledgement

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6. References

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c. The datasets of this study are not available because authers take time to organeze the data but the authors will make every reasonable effort to publish them in near future.