

Measuring the effects of respiratory protective equipment and other protectors in preventing the scattering of vocalization droplets

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Abstract: This study was conducted to quantitatively examine the effects of respiratory protective equipment (respirators) and various other types of protectors in preventing the scattering of vocalization droplets. Each of 12 adult male volunteers was asked to vocalize intermittently for 1 min at a target intensity of approximately 100 dBA in an experimental room adjusted to a humidity of approximately 60–70%. The subjects vocalized while wearing respirators, other types of protectors, or no protectors at all. The droplet concentration in a particle size range of 0.3 to 10 μm was measured under each experimental condition, and the transmitted particle concentration and penetration were calculated. The concentration and penetration of particles transmitted from the respirators were lower than those transmitted from the other protectors examined. The probability of infection reduction through the use of the protectors was estimated from the data obtained on the effectiveness of the protectors in preventing the scattering of droplets. We concluded that there is no need for additional droplet scattering prevention in various work settings when appropriate respirators are used under optimal conditions.

Key words: Airborne particulate matter, Infectious disease transmission, Protective devices, Respiratory infections/prevention

Introduction

In addition to the established infection routes of surface contact, air, and droplets, a new infection route has recent-

ly been drawing attention with the spread of COVID-19. The terms “micro-droplet infection” and “aerosol infection” have come into use to describe this new transmission route, and new infection-prevention measures are now required in conjunction with the other measures conventionally applied.

A review published in 2020 provided a schematic diagram of the particle size distribution of droplets generated

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from a person when coughing, and the distance reached by droplets generated by coughing or sneezing¹). The size and number of droplets expelled by a person greatly depend on factors such as the productive action (coughing, sneezing, vocalization, etc.), the vocalization intensity, gender, and various environmental factors. They are also reported to be bimodal²) and difficulties in droplet measurement have limited the number of reports and produced highly variable results²⁻⁶). Among the droplets expelled by humans, large particles of more than 10 μm in diameter deposit on the floor and walls of a room in a relatively short time, and smaller droplets remain airborne and gradually shrink to a microscopic size through evaporation. There has been some speculation that a microscopic droplet of this type may become a source of infection by floating in air for a long period and becoming the nucleus of a larger droplet. It is also believed to be important to secure a physical distance to prevent infection, as a relatively larger droplet expelled in normal conversation or through coughing can directly reach a distance of 1 to 2 m¹).

According to an analysis of droplet penetration by particle size range in a computational fluid dynamics (CFD) simulation of droplets using the supercomputer FUGAKU⁷), masks are more efficient in collecting larger particles. The investigators performing the analysis calculated the droplet penetration in the CFD simulation based on the particle-collection efficiency of a mask demonstrated experimentally. Their results showed that about 40–50% of the particles smaller than 10 μm corresponded to aerosol leaked from the mask. Further, a mask made from non-woven fabric is difficult to breathe through, which results in a high rate of droplet transmission from the gaps on the sides of the mask and a low rate of transmission through the front. A cloth mask, in contrast, is easy to breathe through, which results in a high droplet transmission from the front. While some behavior analyses of droplets have been carried out through CFD simulations⁸), many experimental studies have been performed to clarify the effects of masks⁹⁻²⁶).

Fischer *et al.* performed optimal imaging experiments to examine the filtration of expelled droplets during speech through the wearing of a face mask or substitute (protector)⁹). Compared to that without a protector, the droplet count was reduced to the following approximate levels by the protectors tested: <1/1,000 by a fit-tested N95 respirator, <1/100 by a surgical mask, <1/20 by a polypropylene mask or polypropylene/cotton mask, <1/10–1/5 by cotton masks of various types, and <1/10–1/5 by a N95 respirator fitted with an exhaust valve. The droplet count while

wearing a neck gaiter was equivalent to that without a protector. With a bandana, the total droplet count exceeded 50% of that without a protector. Rodriguez-Palacios *et al.* applied a bacterial suspension spray simulation model that emitted droplets through a sneezing-like action¹⁰). They investigated the degree to which common fabric masks reduced splashes on a surface placed within 1.8 m, the minimum distance recommended as a “social distance” for protection against SARS-CoV-2 infection, from the emission source. Asadi *et al.* performed experiments with various types of masks using 10 healthy non-smokers (6 men and 4 women) aged 18–45 yr¹¹). Subjects with or without masks were placed in an experimental booth equipped with a droplet-collecting funnel and asked to perform various types of breathing and vocalizations. The number of particles with aerodynamic diameters in a range from 0.3 to 20 μm was counted using an aerodynamic diameter measuring device (APS). Cowling *et al.*, Long *et al.* and Tcharkhtchi *et al.* reviewed the effects of protectors in preventing the splashing of droplets during speech²⁷⁻²⁹). Locke *et al.* systematically reviewed the aerosol transmission of infectious disease and the efficacy of personal protective equipment³⁰). Technical challenges have held back the various experiments done to verify the protective effects of masks and protectors, especially those in which the data verified have been from human subjects.









Our group conducted this study to develop and verify an experimental approach for the assessment of vocalization droplet prevention and to quantitatively evaluate the preventive performance of protectors and respirators. We examined the droplets generated during vocalization before and after various protectors were attached, to measure the change in the number of particles in the particle size range corresponding to aerosol, 0.3 to 10 μm . The target subjects were adult men, as the work space of interest under the grant funding this study was a construction site. We believe, however, that the results can be applied to work spaces of various other types, as well.

Methods

Protectors

Table 1 shows the protectors and respirators used in this study. Three types of protective wear were assessed: masks (the surgical and cloth types most frequently used in Japan), protective devices (a mouth guard, face shield, and neck guard), and respirators (disposable type DS2/N95-equivalent respirator, replaceable type RS2 respirator). The experiments with the surgical mask were performed

Table 1. Masks, protected devices and respirators

	Type	Model	Product	
Mask	Surgical mask	Non-woven fabric	BLISSMEDICAL BLISSMASK BM-MM99T50	
	Cloth mask	Solid urethane	TAKAGI Solid urethane	
Protector	Neck guard	Face cover Cool type	Xingmeng Neck guard	
	Mouth guard	Transparent mask Flat type	Shin Nihon Chemical Ornament MFG Transparent mask Flat type	
	Face shield	Transparent Face shield Free size	FACE SHIELD Face shield Free size	
	Disposable type	DS2	KOKEN HILUCK 350T-11-DS2	
Respirator	Disposable type (with exhaust valve)	DS2-EV	KOKEN HILUCK 355-01-DS2	
	Replaceable type	RS2	3M 3753-RS2	

under two conditions: with the mask worn over the nose and with the nose exposed.

Experimental conditions

The following conditions were set based on the results of the previous research, the performance of the measuring instrument, and preliminary experiments.

1) As the workspace of interest under the grant funding this study was a construction site, the target subjects were adult males (22–50 yr old, 12 persons in total) in the present study. We also took into account the current situation in which most construction workers were male and it was difficult to secure a sufficient number of female subjects due to COVID-19.

2) The particle size range was set to 0.3 to 10 μm . This range corresponded to aerosol, and thus was expected to result in the highest possible rates of particle penetration through the protectors.

3) The subjects were asked to vocalize the vowel “a:” intermittently for 1 min at a target vocalization intensity of 100 dBA, as measured by an NL-21 Sound Level Meter (RION Co., Ltd., Tokyo, Japan) placed beside an optical particle counter (TSI OPS Model 3330; TSI Incorporated, Shoreview, MN, USA).

4) The humidity was adjusted to approximately 60–70% using an air purifier with a humidification function (SHARP KI-EX75W; Sharp Corporation, Osaka, Japan).

Experimental procedure

An outline of the experimental system is shown in Fig. 1. The experiment was conducted in an experimental room equipped with a local exhaust ventilation system (width 2.5 m \times depth 2.0 m \times height 2.0 m = volume 10 m³) equipped with an air purifier. The particle concentration was measured using two optical particle counters: one to measure the particle concentration in the background atmospheric aerosol in the room, the other to measure the droplet concentration in the vicinity of the subject’s mouth during vocalization.

Once the subject was stationed at a predetermined position in the room, an optical particle counters (TSI OPS Model 3330, installed at a predetermined measurement point) quantified the concentration of aerosol in each of the following light-scattering diameter ranges (within the total range of 0.3 to 10 μm): 0.3 μm <, 0.5 μm <, 1.0 μm <, 2.0 μm <, 5.0 μm <. After confirming that these particle concentrations were sufficiently reduced and stable, the droplet concentration measurements were commenced. The experiment was performed several times for each subject using all of the protectors examined.

The background aerosol concentration in the experimental room measured in an unmanned state was greatly affected by the weather and other parameters. Under normal conditions, the number concentration was about 10–70 particles/cm³ for the total particle size range (0.3–10 μm). In sub-ranges within this total, the concentrations were as

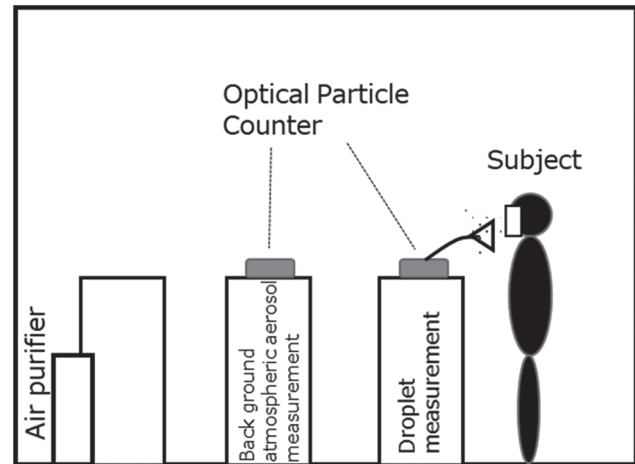


Fig. 1. Experimental setup.

follows: 8–60 particles/cm³ for 0.3 μm <, 1–9 particles/cm³ for 0.5 μm <, 0.1–1 particles/cm³ for 1.0 μm <, 0.02–0.5 particles/cm³ for 2.0 μm <, 0.001–0.01 particles/cm³ for 5.0 μm <. When the air purifier was in operation, the total number concentration of particles was reduced to approximately 2–20 particles/cm³. The concentrations were reduced to the following levels in the respective size ranges: 1.5–17 particles/cm³ for 0.3 μm <, 0.2–2 particles/cm³ for 0.5 μm <, 0.04–0.4 particles/cm³ for 1.0 μm <, 0.01 to 0.15 particles/cm³ for 2.0 μm <, and 0.001 to 0.005 particles/cm³ for 5.0 μm < (listed as reference data in Table 2). Note that the movements of humans in the laboratory during the experiment generated fine particles. The resulting increase in the aerosol concentration, together with fluctuations in time position, may have contributed to experimental error.

Figure 2 shows the timetable for the measurements of the vocalization droplet concentrations in this study. The optical particle sizer (OPS) used to measure the background particle concentration remained in operation throughout the whole experiment, and the OPS for droplet measurement was switched on when the subject arrived at the predetermined measurement position in the room. First, the concentration of generated droplets was measured for 1 min as the subject vocalized without wearing any protector. The protector was then attached, after waiting for a predetermined interval to allow the background aerosol concentration in the room to stabilize. The droplet concentration was then measured at two locations: one at a distance of about 10 cm from the fronts of subject’s mouth (fronts), the other at a distance of about 10 cm from the gaps in the sides of the protector (sides). The particle and droplet concentrations were measured by the OPS at a flow rate of 1 L/min. Finally, the droplet concentration

Table 2. Experimental results on vocalization droplets and atmospheric aerosol

	Particle size range (0.3–10) [μm]	Vocalization droplet	Atmospheric aerosol	Atmospheric aerosol
		[particles/ cm^3] ($N=12$, logarithmic mean \pm 95%CI)	[particles/ cm^3] without air purifier (Concentration range)	[particles/ cm^3] with air purifier (Concentration range)
Number concentration	Total	2.1 \pm 0.3	10–70	2–20
	0.3<	1.4 \pm 0.2	8–60	1.5–17
	0.5<	0.30 \pm 0.05	1–9	0.2–2
	1<	0.13 \pm 0.02	0.1–1	0.04–0.4
	2<	0.10 \pm 0.02	0.02–0.5	0.01–0.15
	5<	0.007 \pm 0.002	0.001–0.01	0.001–0.005

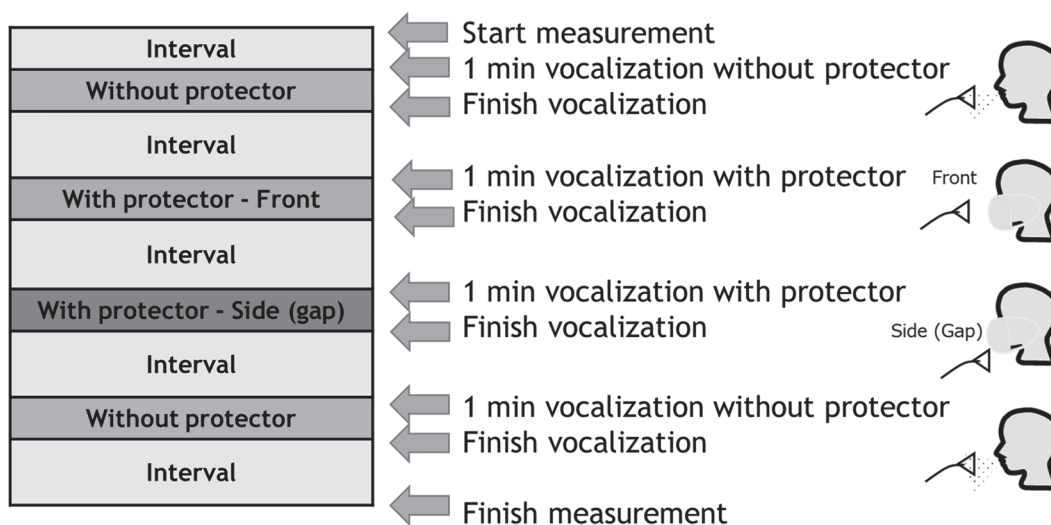


Fig. 2. Timetable for the experiment. First, the concentration of the generated droplets was measured for 1 min as the subject vocalized without wearing any protector. The protector was then attached, after waiting for a predetermined interval to allow the background aerosol concentration in the room to stabilize. The droplet concentration was then measured at two locations: one at a distance of about 10 cm from the front of the subject’s mouth (front), the other at a distance of about 10 cm from a gap in the side of the protector (side). Finally, the droplet concentration was measured again as the subject vocalized without wearing the protector.

was measured again as the subject vocalized without wearing the protector, and the change in the concentration was observed.

Results

First, we quantified the droplet concentration generated during vocalization. Next, we calculated the transmitted particle number concentration and particle penetration through the protectors. The concentration and penetration of particles transmitted from the respirators were lower than those transmitted from the various other protectors examined. The concentration and penetration of particles transmitted from the surgical mask were lower than those from the cloth mask, neck guard, mouth guard, and face

shield. The number of leaked particles increased, however, when the surgical mask was worn with the nose exposed. The details follow below.

Quantification of the droplets generated during vocalization

We will begin this section by describing our method for quantifying the droplets generated (total number concentration of the particles). Figure 3 shows an example of the total number concentration measured using the procedure described in the last section. The horizontal axis shows time and the vertical axis shows the particle number concentration. The dotted and solid lines plot the background particle concentration and the particle concentration during vocalization, respectively. The peaks of the solid lines

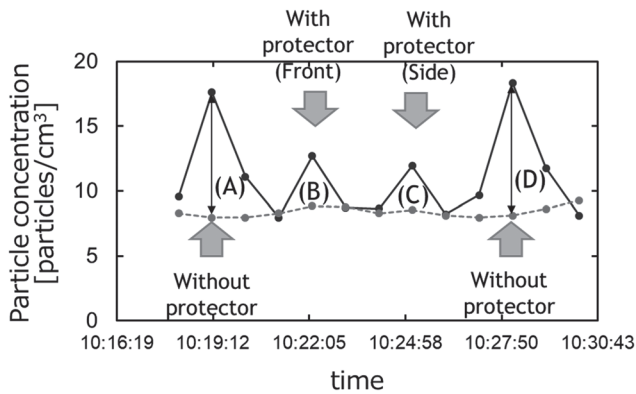


Fig. 3. An example of the experimental results obtained on the total particle number concentration. First, the concentration of generated droplets was measured without any protector (A). The protector was then attached, after waiting for a predetermined interval to allow the background aerosol concentration in the room to stabilize. The droplet concentration was then measured at two locations: one at a distance of about 10 cm from the front of subject’s mouth (front, B), the other at a distance of about 10 cm from a gap in the side of the protector (side, C). Finally, the droplet concentration was measured again as the subject vocalized without wearing the protector (D).

at positions (A) to (D) indicate the particle concentrations, inclusive of the droplet particles, with and without protectors. The number of droplet particles generated with and without protectors can be calculated from the difference (arrow) between the peak of the solid line at each position (A) to (D) and the background particle concentration plotted by the dotted line. The droplet concentration was defined by the following equation.

Droplet concentration
 = (Particle concentration plotted by solid line
 – Background particle concentration plotted
 by dotted line) at (A) to (D) in Fig. 3 (1)

Next, we will describe the relationship between the vocalization intensity and the amount of droplets (total particle number concentration) generated during vocalization, and the variation in the amount of droplets generated. Figure 4 shows the relationship between the vocalization intensity and the amount of droplets observed without a protector. Although the data points showing abundant droplets tend to increase as the vocalization intensity increases, we can see differences between the samples owing to instances of high-intensity generation accompanied by small amounts of droplets. In addition to large individual differences, we may also need to consider the environmental influences. And for data points with extremely high number concentrations, we should also consider the influ-

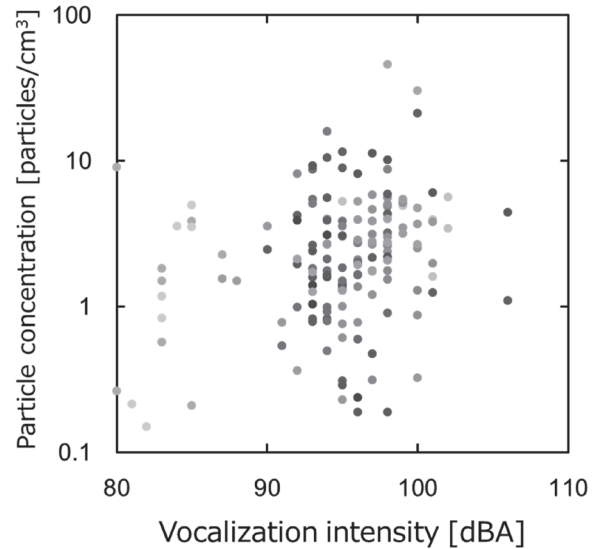


Fig. 4. Relationship between the vocalization intensity and total particle concentration without a protector (plots colored by subject).

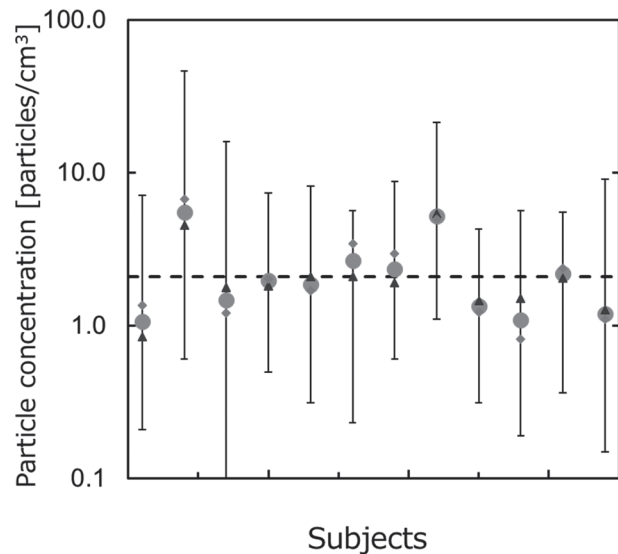


Fig. 5. Fluctuation of the number concentration of vocalization droplets. (●, Total mean; ▲, Mean for (A) in Fig. 3; ◆, Mean for (D) in Fig. 3; bar, max and min.

ence of any pre-existing contamination by atmospheric aerosol.

Figure 5 shows the vocalization droplet concentration for each subject without a protector. The horizontal and vertical axes respectively represent the subjects and droplet levels generated during vocalization (total number concentrations of the particles), expressed as logarithmic means of the particle concentrations in (A) and (D). The

bars are the maximum and minimum values. The total mean value of each subject is about 1–7 particles/cm³, and the variation of each subject is 0–6 times the mean. The dashed line represents the average droplet amount calculated for all subjects. The droplet level at the time of vocalization is thought to be greatly affected by individual differences and the environment. While the data are not broken down for each particle size, the number concentration rises as the particle size decreases and tends to decrease by about an order of magnitude for each stepwise increase in the particle size range. These tendencies are similar to those shown in previous works and previous measurements of atmospheric aerosol.

In addition, the logarithmic mean number concentration of droplets generated during vocalization is 2.1 ± 0.3 particles/cm³ for particles in the total size range. As the particle size increases, the number concentration decreases: 1.4 ± 0.2 particles/cm³ for $0.3 \mu\text{m} <$, 0.30 ± 0.05 particles/cm³ for $0.5 \mu\text{m} <$, 0.13 ± 0.02 particles/cm³ for $1.0 \mu\text{m} <$, 0.10 ± 0.02 particles/cm³ for $2.0 \mu\text{m} <$, 0.007 ± 0.002 particles/cm³ for $5.0 \mu\text{m} <$ (these values are shown in Table 2 for reference). Note, moreover, that the droplet amount generated is much smaller than the concentration of fine particles in the atmosphere shown previously.

Even in the preliminary experiments and previous research, the amount and distribution of droplets during coughing, sneezing, and vocalization vary widely due to individual differences and environmental influences. When the intensity of coughing, sneezing, and vocalization increases, the droplet amount is likely to increase. The difference is several times higher at most, on average, however, and individual differences have a very large influence. For these reasons, we decided to set the target utterance intensity to 100 dBA in our experiments, for guidance. Further, our calculation for the particle penetration took account of the average vocalization particle concentration without a protector for each subject by considering the error in the denominator.

Calculation of the particle penetration

The particle penetration was defined by Equation (2) and calculated by the following method.

$$\text{Penetration} = \frac{\{\text{Droplet concentration (with protector)}\}}{\{\text{Droplet concentration (without protector)}\}} \times 100\% \quad (2)$$

where, the peaks at positions (B) and (C) in Fig. 5 are the particle concentrations measured experimentally at the

fronts and sides of a subject wearing a protector, respectively.

The mean droplet concentrations for each subject without a protector at positions (A) and (D) (shown by a triangle (▲) and rhombus (◆), respectively) are compared with the total mean concentration for each subject (shown by a circle (●)). The experimental fluctuation increases as the total number concentration rises, and the error stays within 30% at maximum. That is, there is almost no difference in the average droplet amount between the measurements taken before the protector was attached ((A) ▲) and measurements taken after the protector was removed ((D) ◆). The mean measured at each measurement time is close to the average for each subject, with an error considerably smaller than the variation of each measured value. Therefore, we calculated the penetration with Equation (3) using the mean concentration of each subject in the denominator of Equation (2).

$$\text{Penetration} = \frac{\{\text{Front (B) Droplet concentration}\} \text{ or } \{\text{Side (C) Droplet concentration}\}}{\{\text{Droplet concentration (without protector) _ mean of each subject}\}} \times 100\% \quad (3)$$

The penetration in each particle size range was determined by the same calculation

Transmitted particle number concentration

Figure 6 (a)–(i) show the transmitted particle number concentrations calculated for each particle size range with the various protectors attached. The results measured from the fronts and sides of the protectors are shown in gray and black, respectively. The error bars indicate the confidence interval (95% CI). Many of the droplets measured in the particle size range corresponding to aerosol (from 0.3 to 10 μm) fell in the particle size range of 0.3 to 1 μm , the range used as the controlling factor for the total number concentration. The absolute value of the number concentration of the transmitted particles of less than 0.5 μm was relatively small for all of the protectors.

As seen from the results of the measurements taken with correctly fitted surgical masks (Fig. 6 (a)) and with surgical masks worn with the nose exposed (Fig. 6 (b)), the leakage of the finest particles was more notable from the gaps around the sides of the mask than from the front. When the masks were attached with the nose exposed, the number of particles leaking from the front increased.

The cloth mask and neck guard were easier to breathe through than the surgical mask, and thus allowed more leakage from the front. While the cloth mask seemed to fit, there were still gaps around the sides of the mask from

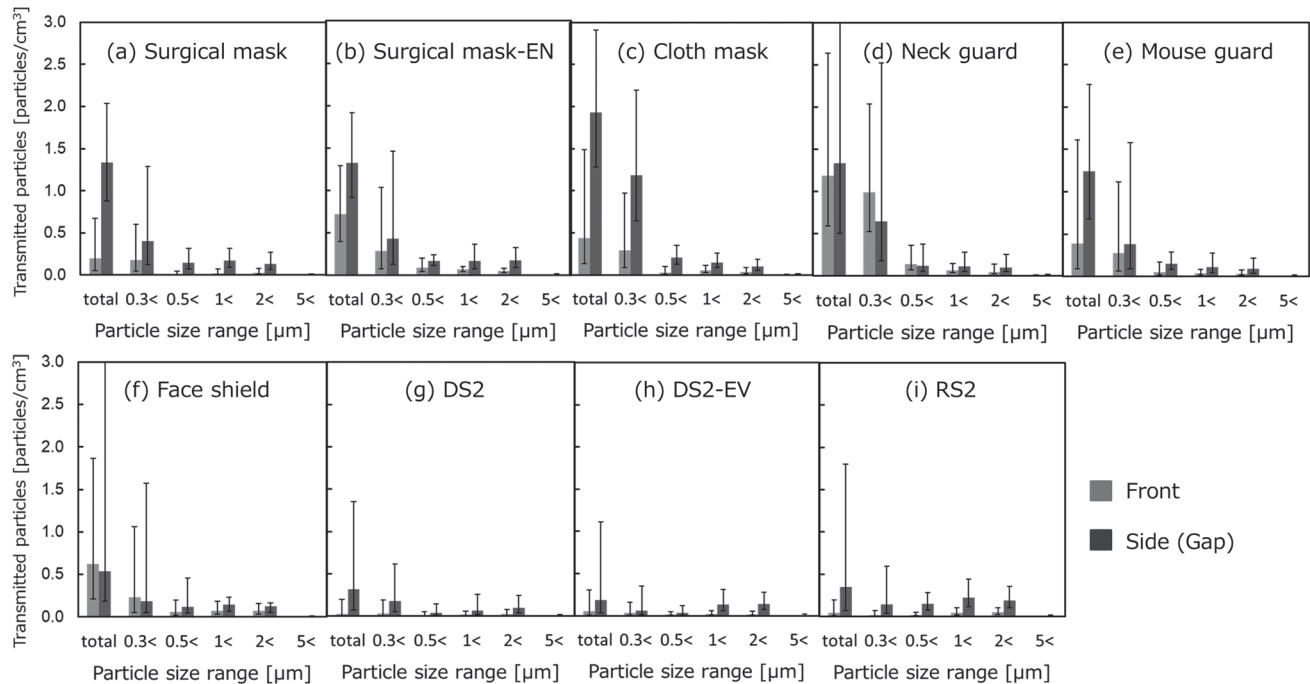


Fig. 6. Experimental results on the transmitted particles (N=12, logarithmic mean \pm 95% CI).

which leaks seemed to occur. The thin fabric of the neck guard, on the other hand, seemed to allow the leakage of particles from every part of the guard.

The mouth guard and face shield had plastic walls directly in front of the face, hence particles were unlikely to splash directly out from the protectors to the front. Compared to the other protectors, however, the distance (space) between the mouth and the mouth guard or face shield allowed the subject to breathe freely, with no resistance. As a result, leakage seemed to occur from all sides of these protectors, leading to a diffusion of particles leaking from the spaces within these protectors.

The respirators, whether disposable or replaceable, or equipped with an exhaust valve or not, allowed the transmission of fewer particles than the other types of protectors. Judging from the observations of the particles in front, some displacement of the respirators was thought to occur when the subjects opened and closed their mouths to produce loud vocalizations. While the performance of the respirators in this state may not reflect strict particle collection, the respirators blocked the transmission of almost all of the droplets in most of the particle size ranges.

Penetration

Figure 7 (a)–(i) show the particle penetrations calculated for each particle size with the various protectors attached. The measurement results from the fronts and sides

of the protectors are shown in gray and black, respectively. The error bars indicate the confidence interval (68% CI; $\pm \sigma$). As the particle size increases in the calculations of penetration, the particle concentration decreases (as denoted in Sections 1 and 3), and the denominator of Equation (1) decreases, as well. On the other hand, the number concentration of droplets in the size range above 0.5 μm was particularly small in the experimental results. Therefore, we note that the chance of contamination with background particle contamination is substantial. For this reason, even one contaminating particle may have had an extremely large effect on penetration, leading to an overestimation of the penetration value. Note, also, that no calculations were done to determine the penetration for the size range over 1.0 μm , as the mean number concentration of droplets generated during vocalization in the size range above 1.0 μm was lower than about 0.1 particles/cm³.

As shown in the results for the surgical masks (Fig. 7 (a) and (b)), the penetration rate was about 30% from the front and exceeded 40% from the sides, when the mask was correctly worn. Particles may have leaked from the gaps on the sides of the mask covering the mouth and nose, as the mask made breathing difficult and easily bunched, creating gaps. In this case, some of the measurement results from the front may actually represent leaks from the sides. In other words, we assume that the higher rate of penetration compared to the simulation result can be explained by

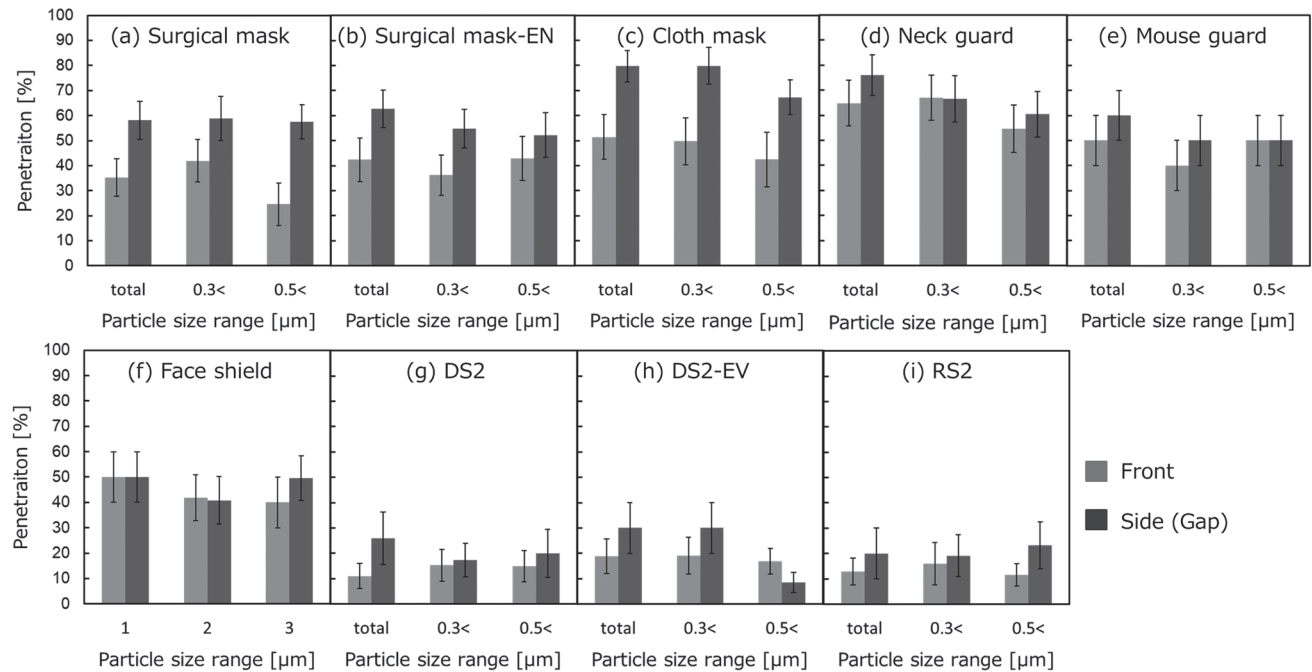


Fig. 7. Experimental results on penetration (N=12, average \pm 68% CI).

difficulty in strictly distinguishing between transmission and leakage in the experiment. When the mask was worn with the nose exposed, on the other hand, the penetration rate was as high as that measured with the mask correctly worn. In addition to exhaling directly from the front, the protruding nose caused the mask to slacken, which tended to allow the formation of many gaps from which leaks were likely to occur.

The cloth mask and neck guard both had coarser pores (SEM images of all protectors are published in the report funded by Health and Labor Sciences Research Grant 2020 in Japan (Grant No. 20CA2043)). They were also more breathable than the surgical mask, and were shown to be relatively leaky, with penetration rates on the fronts as high as about 50–60%. The cloth mask seemed to fit, but parts of it were open. Additional leakage was caused by gaps that seemed to form in the cloth mask, especially when the mouth opened to vocalize. The neck guard was composed of a thin fabric and seemed to slacken in some locations, leading to added leakage beyond that taking place through the neck guard fabric.

The experimental penetration through the mouth guard and face shield varied widely. We believe that the high variability of the results can be attributed to the various open spaces surrounding the plastic plate blocking penetration at the front. The particles were evenly diffused into the room from those spaces, which resulted in extremely

high or low concentrations of experimental particles in the front in some cases. The average penetration rate was about 40–50%, approximately matching those of the cloth mask and neck guard. Caution in interpretation is due here, however, as our experiment may have not fully captured the behavior of the leaked particles.

As mentioned in our results on the transmitted particle number concentration, almost no vocalization droplets were observed in the assessments of the respirators. The penetration rates were as low as 10–20% on both the fronts and sides of the respirators. The high particle collection performance of the respirators strongly prevented the scattering of droplets.

Discussion

Table 3 shows the logarithmic mean of the number concentration of transmitted particles and the particle penetration rate obtained experimentally for each subject, and the 68% CI and average particle penetration rate. The number of transmitted particles is expressed to 2 to 3 digits after the decimal point, and the particle penetration rate is expressed as an integer.

As mentioned previously, since the droplets generated from human vocalization are unstable and the amounts and distributions have poor uniformity, an accurate comparison cannot be unconditionally performed. When the values

Table 3. Experimental results on the splash-preventive effects of various protectors averaged transmitted particles and penetration (N=12)

Type	Size range [μm]	Transmitted particles [particles/cm ³] (logarithmic mean)		Penetration [%] (average \pm 68% CI)	
		Front	Side	Front	Side
(a) Surgical mask (non-woven fabric)	Total	0.2	1.34	35 \pm 8	58 \pm 8
	0.3<	0.18	0.4	42 \pm 9	59 \pm 9
	0.5<	0.01	0.15	25 \pm 8	57 \pm 7
	1<	0.02	0.17	-	-
	2<	0.024	0.14	-	-
	5<	0.002	0.008	-	-
(b) Surgical mask, exposed nose (EN) (non-woven fabric)	Total	0.72	1.33	42 \pm 9	63 \pm 7
	0.3<	0.29	0.43	36 \pm 8	55 \pm 8
	0.5<	0.094	0.72	43 \pm 9	52 \pm 9
	1<	0.07	0.17	-	-
	2<	0.054	0.18	-	-
	5<	0.0004	0.01	-	-
(c) Cloth mask (urethane)	Total	0.44	1.93	51 \pm 9	80 \pm 6
	0.3<	0.29	1.19	50 \pm 9	80 \pm 7
	0.5<	0.03	0.21	40 \pm 10	67 \pm 7
	1<	0.051	0.15	-	-
	2<	0.037	0.097	-	-
	5<	0.002	0.005	-	-
(d) Neck guard	Total	1.19	1.34	65 \pm 9	76 \pm 8
	0.3<	0.99	0.65	67 \pm 9	67 \pm 9
	0.5<	0.14	0.12	55 \pm 9	60 \pm 9
	1<	0.067	0.11	-	-
	2<	0.043	0.1	-	-
	5<	0.004	0.009	-	-
(e) Mouth guard	Total	0.39	1.24	50 \pm 10	60 \pm 10
	0.3<	0.28	0.38	40 \pm 10	50 \pm 10
	0.5<	0.054	0.15	50 \pm 10	50 \pm 10
	1<	0.036	0.11	-	-
	2<	0.034	0.09	-	-
	5<	0.003	0.008	-	-
(f) Face shield	Total	0.63	0.54	50 \pm 10	50 \pm 10
	0.3<	0.23	0.18	42 \pm 9	41 \pm 9
	0.5<	0.056	0.12	40 \pm 10	50 \pm 9
	1<	0.074	0.15	-	-
	2<	0.07	0.12	-	-
	5<	0.003	0.005	-	-
(g) Disposable type DS2	Total	0.027	0.32	11 \pm 5	30 \pm 10
	0.3<	0.031	0.18	15 \pm 6	17 \pm 7
	0.5<	0.012	0.037	15 \pm 6	20 \pm 9
	1<	0.016	0.066	-	-
	2<	0.022	0.1	-	-
	5<	0.002	0.004	-	-
(h) Disposable type (with exhaust valve) DS2-EV	Total	0.057	0.19	19 \pm 7	30 \pm 10
	0.3<	0.031	0.062	19 \pm 7	30 \pm 10
	0.5<	0.015	0.033	17 \pm 5	9 \pm 4
	1<	0.022	0.14	-	-
	2<	0.016	0.14	-	-
	5<	0.002	0.008	-	-
(i) Replaceable type RS2	Total	0.04	0.35	13 \pm 5	20 \pm 10
	0.3<	0.014	0.15	16 \pm 8	19 \pm 8
	0.5<	0.019	0.15	12 \pm 5	23 \pm 9
	1<	0.041	0.22	-	-
	2<	0.05	0.19	-	-
	5<	0.002	0.008	-	-

CI: confidence interval.

are converted to particle penetration by Equation (3), the results are in good agreement with the simulation results⁷⁾. While the face shield and mouth guard are fitted with protective plastic sheets directly in front of the mouth, the diffusion range of the scattered droplets is wide due to the large release space. We cannot rule out an underestimation of the penetration, as our instruments may have failed to completely capture the widely diffused particles.

The non-woven surgical masks and respirators were highly effective in preventing the scattering of particles. Our findings suggested, however, that particles may have escaped preferentially from pathways, such as the gaps that formed. In addition, the collection performance of a filter was usually higher for larger particles, and large particles were thought to be collected by inertia even when leaks were observed. Further, the atmospheric concentration of particles of the size produced by vocalization was relatively high. Considering the large influence of the contaminating particles, the leaked exhaled air may have entrained the surrounding air, and the atmospheric aerosol within the entrained air may have been counted as droplets. We should therefore note that the true particle leakage rate of $1 \mu\text{m} <$ is quite small, as the denominator is small and the penetration may be overestimated.

The splash-prevention effects of the thick but coarse cloth mask and the neck guard composed of thin fabric were not as remarkable as that of the non-woven surgical mask, which was generally consistent with the results of previous research. Although the mouth guard and face shield had large open spaces, the plastic sheets at the fronts of these protectors blocked the direct splashing of droplets. The experimental results varied widely, however, and the splashing droplets spread in directions other than the front. The mouth guard and face shield did not robustly prevent the splashing of droplets, and they cannot be expected to be effective in preventing the spread of infectious diseases. The appropriate use of effective protectors is recommended in indoor workspaces with poor ventilation.

Finally, we conducted a simulation to estimate the relative effect of the protectors in reducing the infection probability by preventing the scattering of vocalization droplets in a lecture room populated by 80 students, including a spreader, based on an earlier experiment by Ochiai *et al.* to examine the ventilation efficiency of carbon dioxide concentration measurements³¹⁾. First, we estimated the carbon dioxide concentration in the room based on the breath volume, ventilation volume, and room volume, assuming a perfect mixing model. Next, we estimated the infection probability in the room using the Rudnick & Milton model

based on the Wells–Riley equation^{32, 33)}.

$$P (IP) = \left[1 - \exp \left(- \frac{\bar{f} q p t}{n} \right) \right] \times 100\% \quad (4)$$

where, P is the infection probability (IP), f is the re-breathing ratio, q is the quanta generation rate, p is the penetration, t is time, and n is the number of persons.

One of our earlier reports described the combined use of a perfect mixing model and the Rudnick & Milton model, for application to a lecture room³⁴⁾. The quanta generation rate was assumed to be 500, as it was proposed to be about 15–1,000 for COVID-19^{35–37)}. The penetration was set to 0.65 for the cloth mask, assuming a 5 to 5 flow ratio between the front and side (front:side=5:5), 0.56 for the surgical mask (front:side=1:9), and 0.12 for the DS2 RPE (front:side=9.5:0.5), based on the experimental results.

Figure 8 shows the calculated carbon dioxide concentration and infection probabilities in the simulated lecture room. The change of carbon dioxide concentration was accurately represented by the model. From the results of the change in the estimated relative infection probability, appropriate ventilation was found to be one of the most effective measures for infectious disease control. Within a ventilated environment, the wearing of a cloth mask or surgical mask by the spreader is expected to reduce the infection probability by an additional 8% (from 23% to 15%) and 10% (from 23% to 13%), respectively. The wearing of the RPE DS2/N95 respirator by the spreader is expected to reduce the infection probability by an additional 20% (from 23% to 3%).

The Centers for Disease Control and Prevention (CDC) points out that it is effective to wear a cloth mask on top of a surgical mask (double masking)³⁸⁾. A surgical mask tied behind the ears is also fashioned with folds to reduce gaps and reduce leaks. A normal mask, however, has a sufficient effect, and the degree to which a double mask improves the infection suppression effect is unknown. Further, the doubling of disposable masks such as surgical masks, and the layering of other masks on top of N95 masks, are not recommended.

Conclusion

All of the protectors examined in our experiments to assess their droplet-prevention effects showed some effect in preventing droplets within the particle size range corresponding to aerosol, the range we measured.

The protectors that were less easy to breathe through

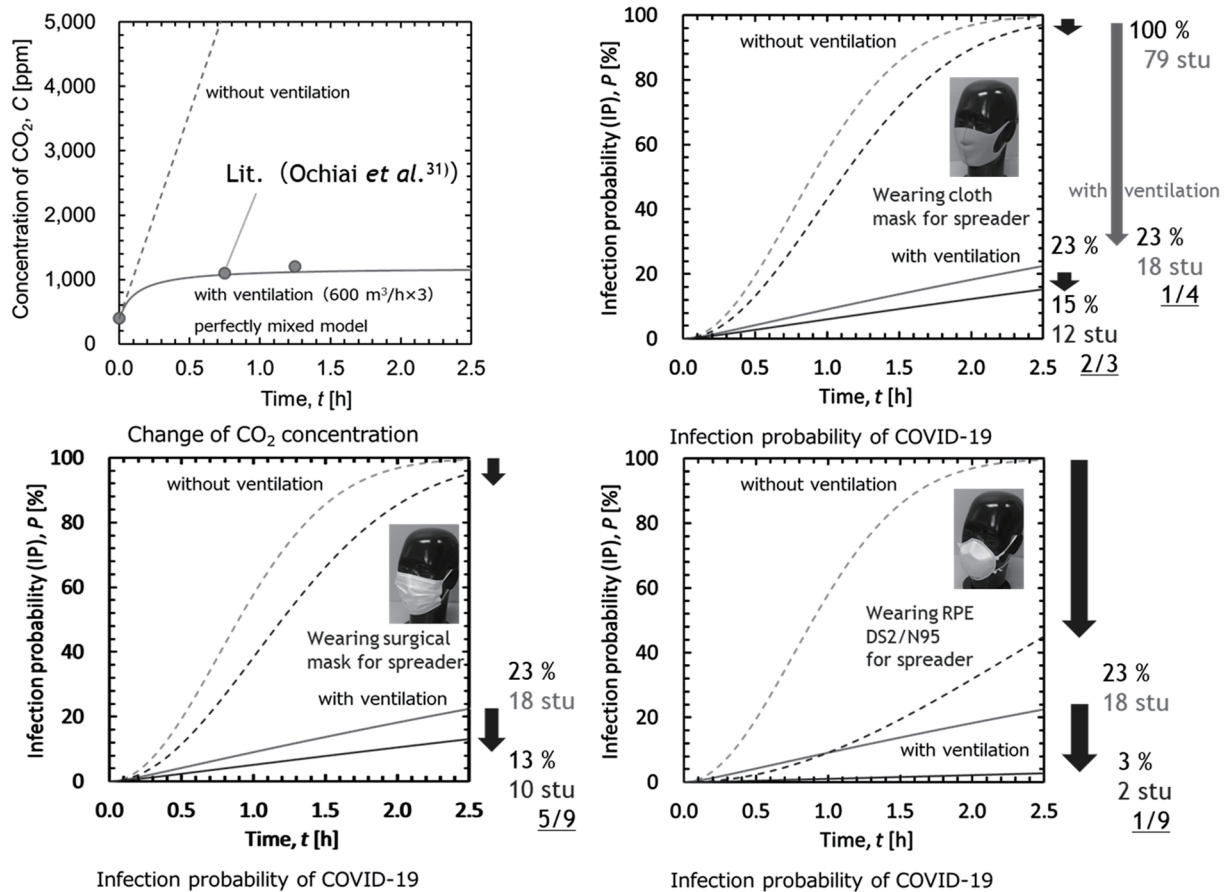


Fig. 8. Estimated results on the carbon dioxide concentration and infection probabilities in the simulated lecture room.

than the surgical mask and respirators, and significantly decreased leakage from the front during vocalization with a loud voice. Leakage from the sides due to gaps or the like caused by misalignment remained distinctly possible, however, under the loud vocalization condition. We concluded that a subject wearing a respirator did not require additional droplet prevention, provided that the respirator was appropriate and was used under optimal conditions.

The cloth protectors that were relatively easy to breathe through, namely, the cloth mask and neck guard, leaked more from the front than the surgical mask and respirators, by dint of their high breathability.

The mouth guard and face shield showed the same level of penetration as the cloth mask and neck guard. The structure of these protectors, however, prevented direct splashing to the front while allowing large open spaces elsewhere. This structure permitted the particles to move with a high degree of freedom, thus allowing a free scattering of droplets in complicated patterns. Caution must therefore be taken in interpretation, as the leaked particles may be impossible to trace experimentally.

Based on our results, we would only strictly recommend the wearing of a mask indoors, or in a crowded situation where ventilation tends to be insufficient. If distance is sufficiently maintained between people, the wearing of masks outdoors does not appear to be necessary. In addition to the experimental results and simulation results of the present and previous research, the work environment and usability of the protectors should be comprehensively considered. We recommend that working persons select protectors that are optimally suited for the types of work they perform and their work space environments.

Disclosures

Approval of the research protocol: This study was approved by the Ethics Committee of the University of Occupational and Environmental Health, Japan in 2020 (Reference No. R2-028). *Informed consent:* Written consent was obtained from all participants. *Competing interest statement:* The authors have no competing interests to declare.

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