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Effectiveness of Various Face Coverings on Controlling Particle Emissions during Speaking

Abstract:

Public health authorities have mandated wearing face coverings indoors as a tool for preventing the spread of COVID-19. Since then, people have worn various face coverings, including masks and respirators, when such mandates have been in effect. While masks and respirators reduce respiratory particle emissions, various studies indicate that the efficiency of face coverings can vary substantially. Here, we characterized the outward particle emissions from a real person's speaking activity while wearing various cloth masks, surgical masks, respirators, bandanas, and neck gaiters in different wearing styles. In addition, we evaluated adding extra filters to cloth masks, crossed ear loops for surgical masks, and double masking (cloth over surgical). Cloth masks, surgical masks, respirators, and double masking reduce the outward particle emission rates on average by 43.8%, 79.7%, 88.4%, and 86.4%, respectively, for speaking. For all three types of surgical masks, crossing the ear loop did not yield a significant particle reduction compared to the standard wearing style. In contrast, the particle emission rates from two types of cloth face coverings—a bandana and two different neck gaiters—were greater than that for wearing no masks, suggesting that some face coverings shed non-respiratory particles. We also characterized the particle emission rate and size distribution from rubbing the masks against themselves and against human skin to quantify the non-respiratory particle emission from friction during speaking. Our results show that cotton made face coverings tend to emit more non-respiratory particles than non-cotton made face coverings during speaking. The skin particles emission rates were similar to the non-cotton made face coverings, with particle size typically smaller than 0.58 μm. Furthermore, we characterized the non-respiratory particle emission by flowing particle-free air through the masks. The non-respiratory emission from the hand rubbing experiments and clean-air flow experiments had a positive linear correlation, suggesting cloth masks tend to emit more non-respiratory particles by themselves due to the friction and air flow than respirators and surgical masks. The non-respiratory particle emission level is strongly correlated with the mask material. Additionally, the hand rubbing experiments had higher particle emission in the range of 2-15 μm compared to the speaking activity, which primarily produced particles in the range of 0.5-2 μm, indicating the non-respiratory particles were smaller on average than respiratory particles. Overall, our results provide further evidence that wearing masks can reduce the outward particle emissions, but with the efficacy dependent on the mask type.

1. Introduction:

Airborne infectious diseases can be carried by aerosol particles entrained in airflows produced during respiratory activities[1–3]. Respiratory activities include breathing, speaking, and coughing, which lead to the emission of particles at different rates[4]. For speaking, the particle emission rate depends mainly on the vocalization amplitude, albeit with substantial person-to-person variability[5,6]. Face coverings, such as masks and respirators, can block the emission of airborne infectious diseases from respiratory activities as well as the reception of particles during inhalation[7]. The efficiencies of different face coverings vary substantially depending on the mask material and fit, as demonstrated by measurements of the material filtration efficiency, airflow resistances, fit factors associated with inhalation, and source control tests conducted with masks placed on manikins[8,9]. However, few studies have characterized the effectiveness of face coverings for source control (i.e., the reduction of exhaled respiratory particles) when worn by people while engaged in an everyday respiratory activity, speaking[5,10,11]. Such measurements provide an indication of the actual performance of face coverings under realistic conditions, which may not be fully captured by other experimental methods. For example, the US Centers for Disease Control (CDC) recommended that the efficiencies of medical procedure (surgical) masks could be improved by knotting and tucking the ear loops or adding a cloth mask over the top of the surgical mask through tests with manikins[12]. Yet the benefits of these strategies with real wearing are not well established[13].

Additionally, certain face coverings may shed fibers during use, such as masks fibers and human skin[4,14]. These non-respiratory aerosolized fomites may carry deposited viruses[15,16], and such effects are not characterized using standard methods[4,17]. Fiber shedding can also confound determination of mask efficiency. Further, abrasion of the skin by the mask material can lead to release of skin particles[18,19], an under-considered factor in mask efficiency studies. There remains a need for a comprehensive investigation of the source control efficiency towards respiratory emissions of various masks to understand better their likely performance and effectiveness in real-world situations.

Here, our experiment focuses on measuring respiratory particle emissions by real people speaking, wearing five common types of masks used by the public: reusable cloth masks, surgical masks, respirators, a bandana, and neck gaiters. For one of the cloth masks, we also considered the impact of adding internal filters. Additionally, we examined the particle emission rate and size distribution from different masks material with manual rubbing (against face coverings themselves and human skin) and flowing air through the masks tests, exploring the potential non-respiratory aerosol emissions.

We conducted a systematic investigation of the effectiveness of a wide range of face covering types in terms of their control of respiratory particles produced during speaking when worn by a human participant. Specifically, we characterized and compared the emission rates and concentrations of particles produced during speaking with and without wearing various mask types. We also characterized the concentration of particles produced during the mechanical rubbing against face coverings themselves and using a surgical mask (low non-respiratory particle emission) rubbing against participant's lip and mouth.

2. Methods:

The experimental methods generally follow from the previous efforts[4,20] and are described below.

2.1 Human participant: Experiments were performed by one participant, a 23-year-old, healthy, self-identified male. Previous studies indicate there is substantial person-to-person variability in respiratory particle emission rates.[5,10] For instance, some individuals tend to emit more particles than others during speaking, even at a constant loudness. The person-to-person variability greatly exceeds the variability between different trials from a single individual, at least with no mask wearing[20]. Nonetheless, as previous investigations of mask efficiencies demonstrate that the median results from repeated measurements from one individual generally track those from a cohort, the results here should provide a reasonable indication of the relative effectiveness different mask types.

2.2 Face Coverings detail: All face coverings and filter inserts were commercially purchased. Table 1 provides details. In brief, we considered multiple versions of five of the most commonly used types of face coverings by the public: reusable cloth masks, surgical masks, N95 and KN95 respirators, bandanas, and neck gaiters. The material and fitting details differ between each type of mask and sometimes between masks of the same type. Photographs of each mask secured on a manikin are shown in Fig. 1 for reference. The particle reduction efficiency was determined for each of these mask types with standard wearing. All the masks have ear loops or head loops to hold them in place, except the bandana and neck gaiters. For masks that had nose strips, these were molded around the participant's nose through gentle pinching with two fingers.

One of the masks, the "Tommie Copper" cloth mask (TC), allowed for the insertion of an additional filter. Using this mask, we characterized the impact of two types of filter inserts (TC-A: one layer of polypropylene filter manufactured by Airflow Product ASIN; TC-P: A $PM_{2.5}$ filter with five layers of cloth and activated carbon filter manufactured by JCBABA) on the particle reduction efficacy. We also assessed the impact of wearing surgical masks following the CDC recommendations[12,21]: simply crossing the ear loops and "double masking" with a cloth mask on top. For double masking, we used a black surgical mask (SB) inside that was covered with a

Tommie Copper (SB-TC) or Hanes Black cloth mask (SB-HB) on the outside. For the bandana, we folded it along the diagonal and tied an overhand knot on the back of the head to cover the nose and mouth as tight as possible. The neck gaiter was worn such that it encompassed the head and ensured the nose and mouth were well covered.

***2.3 Experimental setup*:** The general experimental setup used was similar to that in the previous work[20]. The participant speaks in front of a plastic funnel (19.5cm diameter) connected directly to an aerodynamic particle sizer (APS, TSI model 3321) and sampled at a T-junction to a mixing condensation particle counter (MCPC, Brechtel Manufacturing). Due to the sharp turn, the MCPC might underestimate large-size particles (>PM_{10}) because large particles might have too large inertia to make the turn. However, the APS is the primary particle size and number measurement tool, and the large-size particle loss will not affect the APS measurement.

The funnel and instrumentation are located inside a HEPA-filtered laminar flow hood, which provides an extremely low background particle environment (<0.04 particles/cm^3 measured by MCPC during the laminar flow hood operating time). The APS measures the number concentration and size distribution of particles between 0.583 μm to 19.8 μm in aerodynamic diameter and samples with a 5 lpm total flowrate and sample flowrate of 1 lpm. The MCPC characterizes the overall number concentration of all sampled particles >10 nm and samples with a 0.37 lpm total flowrate. We refer to measurements from the APS as "large particles" and from the MCPC as the "total particles." An additional 20 lpm of flow is pulled through the funnel along with the flow to the MCPC to decrease the particle residence time. The typical human average volumetric flow rate during speaking ranges from 12 - 42 lpm at peak values[22], with a time-average value around 13 lpm[23], less than the 25 lpm total sample flow. As such, the measured particle concentrations are diluted by about a factor of two relative to the true concentration. The funnel covers the participant's jaw and bottom of the eyes during the speaking activity. The participant places the mouth inside the funnel entrance during speaking and mask rubbing. Additionally, typical relative humidity values in the laminar flow hood were ~30-45%. As such, we expect that the particles will have nearly completely dried from their initially hydrated state in the time it takes for the particles to transit to the particle detectors[5].

2.4 Particle emission via speaking. The human subject reads the Rainbow passage, a 330-word linguistic text (Supplementary Text S1) with a wide range of phonemes at an intermediate, comfortable voice loudness in front of the funnel. The average speaking duration is 2 minutes and 10 seconds. The vocalization amplitude is recorded by a microphone located right on the outside of funnel edge. To count the actual particle emission during speaking, we assumed that only the vocalization period will produce aerosols, corresponding to the high loudness amplitude shown in Fig. S2. The speaking period percentage here ranged from 60-70%. A total of 5-8 trial replicates were conducted for each mask and wearing style, and each repeat was tested in different days. After each testing set, participant store the used mask in different plastic food storage bags in order to minimize the particle contamination.

2.5 Non-respiratory particle emission via hand-rubbing. Following from Asadi et al.[4], particle generation during rubbing of each mask was characterized. The participant used their thumb and index finger to fold and rub the mask material against itself using a circular movement in front of the APS inlet. Each mask was rubbed for 15 seconds, using the best effort to generate the same pressure for every mask. The same rubbing procedure is repeated 3 times for each mask. Geometric averages are calculated from the three replicates.

Emission of non-respiratory particles produced from rubbing of skin was also characterized. As far as we are aware, these are the first experiments considering shedding of skin particles under induced friction. Here, a participant used the fitty (FY) surgical mask (which showed low non-respiratory particle emission) and used one hand to rub against (i) the bridge of the nose ("Nose") and (ii) the upper lip ("Lip") for approximately 35 seconds with constant pressure. The same skin-Black surgical mask (SB)rubbing test was repeated three times each for the nose and mouth, with geometric averages reported.

2.6 Non-respiratory particle emission via clean flowing air. Each mask was measured by APS after secured over the APS sampling tube (0.9 cm diameter) for 15 s. Given a total flow rate of 5 lpm, the clean air (under the laminar flow hood operation time) velocity into the sampling tube is 0.13 m/s. For general human speaking, the mouth opening area is approximately 1.8 cm^2 for speaking on average (5.0 cm^2 at peak), which has similar area with APS sampling tube cross section area (~2.5 cm^2)[24], and the average speaking air velocity (~0.8 m/s) is higher than the APS sampling air velocity (0.13 m/s)[22]. However, during speaking, the air flow is periodic (active speaking) and the overall averaged velocity might be lower than 0.8 m/s[22,23]. The same clean flowing air procedure was repeated 6 times for each mask. This experiment characterizes the tendency of the mask materials to release particles simply from air passing through them.

2.7 Statistical and data analysis. Box-and-whisker plots show the 10, 25, 50, 75, and 90 percentile, interquartile range (black box), and range (black whiskers). All differences between the speaking particle emission rate are calculated by single-factor ANOVA test, assuming the confidence interval is 95% (α=0.05).

Particle emission rates ($\dot{N}_p$, p/s) are characterized as particles per second as measured by the instrumentation, for the APS that characterizes larger particles ($\dot{N}_{p,>0.58\mu m}$) and for the MCPC that characterizes particles independent of size ($\dot{N}_{p,tot}$). These can be converted to particle concentrations (C_p, p/cm^3) by dividing by the sample flow rate for the instrument (1 lpm = 16.67

cm^3/s for the APS and 0.37 lpm = 6.17 cm^3/s for the MCPC). Particle reduction extents are characterized as ratios (R_{mask}) by dividing the $\dot{N}_p$ measured with mask wearing by the corresponding measurement without mask wearing. These ratios are related to the reduction efficiency as $\eta_{mask} = 1 - R_{mask}$.

3. Results and Discussion

3.1 Rubbing experiment:

Emission of friction-generated non-respiratory particles from the masks or skin during the speaking experiments can increase observed particle concentrations during mask wearing experiments relative to the no mask reference. This can lead to apparently lower mask efficiencies compared to if only respiratory particles were measured, as noted by Asadi et al.[4]. To further understand the potential impact of non-respiratory particle emissions, at least in a relative sense, on the speaking experiments we first consider the results of the rubbing experiments. For reference, the measured background (BLANK) concentrations were $C_{p,<0.58\mu m}$ = 0.0 p/cm^3 (no particles observed) and $C_{p,tot}$ = 0.01 p/cm^3.

3.1.1 Cloth masks: For the cloth masks (Fig 2a), the particle emissions for large particles during rubbing of three cloth masks (HB, HW, COL) (Table 1) were the highest: $C_{p,<0.58\mu m}$ = 13.6 p/cm^3, 9.5 p/cm^3, and 6.7 p/cm^3, respectively. The particle size distributions for these masks were broad, with the majority of particles in the range 0.6 - 10μm (Fig. 3a). The total particle emissions for these masks were similarly large, with $C_{p,tot}$ = 14.3 p/cm^3, 12.7 p/cm^3, and 8.7 p/cm^3, respectively (Fig. 2b). Thus, the majority of the particles emitted for these masks are contained in the larger particles, with $C_{p,>0.58\mu m}/C_{p,tot}$ = 0.95, 0.75, and 0.76, respectively, and consistent with the observed size distributions. The Hanes Black(HB) and Tultex White(HW) masks are both 100%

cotton while the Columbia (COL) mask is a polyester/elastane blend. The other two cloth masks (LAP and TC) (Table 1) had significantly lower large and total particle emissions: $C_{p,>0.58\mu m}$ = 0.7 p/cm^3 and 0.5 p/cm^3 and $C_{\text{p,tot}}$ = 2.4 p/cm^3 and 3.3 p/cm^3, respectively, and with a smaller contribution of large particles, with $C_{p,>0.58\mu m}/C_{p,tot}$ = 0.31 and 0.17, respectively (Fig. 2). The LAP is 100% polyester while the Tommie Copper (TC) has a polyester/elastane shell with a polyester/cotton blend lining.

Most likely, the comparably larger rubbing-induced emissions for the Hanes Black(HB) HB and HW masks is due to cotton having a greater propensity to shed than the polyester blends. However, this would not explain the substantial difference between the polyester Columbia (COL) mask and the LAP and Tommie Copper cloth masks (TC), a result that is somewhat surprising given that the TC mask has a polyester/cotton blend liner. Despite the similar materials for the Columbia (COL) and TC mask shells the Columbia (COL) mask was qualitatively rougher, which could potentially explain the difference. Asadi et al. (2020) also found that some masks emit more non-respiratory aerosols, which generally dominate the larger size range[4].

3.1.2 Bandana and Neck Gaiters: For bandana (BAN) (Table 1), the large particle emission during rubbing averaged $C_{p,>0.58\mu m}$= 21.8 p/cm^3 while the Buff neck gaiters (BUF) and Turtle Fur neck gaiters (TUR) (Table 1) were only $C_{p,>0.58\mu m}$= 2.3 p/cm^3 and 0.6 p/cm^3 (Fig. 2). The total particle emissions were similar, with average $C_{p,tot}$= 19.1 p/cm^3 for bandana (BAN) and $C_{p,>0.58\mu m}$= 5.0 p/cm^3 and 1.7 p/cm^3 for BUF and TUR, respectively. This yields $C_{p,>0.58\mu m}/C_{p,tot}$ = 1.14, 0.46, and 0.35 for BAN, BUF, and TUR, respectively. The large ratio for BAN is consistent with the observed size distribution (Fig. 3b). BAN is made from 100% cotton, similar to Hanes Black (HB) and Tultex White(HW), while Buff neck gaiters (BUF) and Turtle Fur neck gaiters (TUR) are made of polyester blend and spun acrylic fleece, respectively. The similarity of the bandana (BAN) emissions and large-to-total particle ratio to the HW and Hanes Black(HB) results, and the comparably low emissions for the Buff neck gaiters (BUF) and Turtle Fur neck gaiters (TUR) provides further support for the idea that cotton material tends to shed more, and larger non-respiratory particles than the polyester blend material.

3.1.3 Respirators: For the respirators rubbing experiment (Fig. 2), the average large particle emissions were $C_{p,>0.58\mu m}$ = 0.03 p/cm^3, 0.005 p/cm^3, 0.02 p/cm^3, and 0.05 p/cm^3 for the KN95, T92, ALG, and T85V (Table 1), respectively, and with $C_{p,tot}$= 5.6 p/cm^3, 0.7 p/cm^3, 0.06 p/cm^3, and 0.05 p/cm^3, respectively. The $C_{p,>0.58\mu m}/C_{p,tot}$ ratio showed that the respirators also shed 99% small particles (<0.58μm). Differences in materials (Table 1) likely explains the very different and much smaller $C_{p,>0.58\mu m}/C_{p,tot}$ for the respirators versus the cloth masks, bandana, and neck gaiters.

3.1.4 Surgical masks: The average large particle emissions were $C_{p,>0.58\mu m}$ = 0.06 p/cm^3, 0.02 p/cm^3 and 0.01 p/cm^3 for ChaX surgical masks(CX), Black surgical masks(SB), and Fitty surgical masks(FY) (Table 1), respectively (Fig. 2a), and with total particle emissions of $C_{p,>0.58\mu m}$ = 2.8 p/cm^3, 0.7 p/cm^3 and 0.3 p/cm^3, respectively. The total emissions from rubbing of the surgical mask was similar to that from the respirators and with the vast majority of emitted particles being <0.58 μm. This is presumably due to the material does not contain any cotton and the extra non-woven and non-latex fabrics on the shell protected the inner layer from friction.

3.1.5 Skin: Another potential source of non-respiratory particles is from rubbing of the mask material against the participants skin, liberating skin fragments or skin-associated microbiota[25]. The averaged particle emissions for "Nose" was $C_{p,>0.58\mu m}$ = 0.2 p/cm^3 and for "Lip" was $C_{p,>0.58\mu m}$ = 0.9 p/cm^3 (Fig. 2a). The size distributions from the "Nose" and "Lip" rubbing were strongly skewed towards particles smaller than 2 microns (Fig. 3e). This implies that particles from skin shedding exist primarily in the small-particle size range, which is also supported by the $C_{p,>0.58\mu m}/C_{p,tot}$ of Nose and Lip: 0.06 and 0.03 (Fig. 2c).

3.1.6 Summary: Overall, the cloth masks, including the bandana and neck gaiters, tended to have the largest particle emissions with rubbing. Cotton masks tended to have the highest emissions among this group. A large proportion of the emitted particles from these masks were >0.58 µm, and in some cases nearly all of the particles were >0.58 µm. Large particle emissions from surgical masks and respirators were comparably small, and in stark contrast to the cloth masks the vast majority of the particles emitted were small (<0.58 µm). Rubbing of the face led to total particle emissions similar in magnitude to most of the non-cotton cloth masks but with the majority of particles emitted being small rather than large.

3.2 Clean-air flow experiment:

We quantified the non-respiratory particle emissions when particle-free air flowed through each mask, without rubbing. Similar to the rubbing experiments, with flowing air the three cotton-made cloth face coverings (HB, HW, and bandana (BAN)) emitted the greatest amount of non-respiratory particles, with $\dot{N}_{p,>0.58\mu m}$= 0.58 p/s, 0.67 p/s, and 1.2 p/s (Fig. 4). The particle size was mainly under 5 µm for the HB and HW cotton masks, while the bandana (BAN) emitted particles from submicron to 15 µm (Fig. 5). This difference is consistent with the rubbing experiment and indicates that even though the material is same, a difference in the mask structure might affect the size of the emitted non-respiratory particles. The surgical masks and respirators had the lowest non-respiratory particle emissions from flowing air in all size range. The observed particle emissions from flowing air for the various face-covering types was generally consistent with the rubbing experiment (Fig. 4). However, the magnitude of non-respiratory particle emission from flowing air was significantly lower than rubbing with two orders of magnitude on average. This suggests that friction between masks and the face during wearing might be the predominant source of non-respiratory particles, as opposed to air flowing during exhalation. However, we only tested steady air flow. During the vocalization, the air puffs might generate additional fiber friction and cause excessive non-respiratory particle emission from masks.

3.3 Speaking Experiment:

Results for the speaking experiments are considered below, grouped by mask type. We primarily present particle emission rates for consistency with previous studies, although also report equivalent particle concentrations to facilitate comparison between the large and total particle results.

3.3.1 No mask: The particle emission rates for large particles (>0.58 µm) during speaking with and without mask-wearing are shown in Figure 6. Results for all particles are similar (Fig. S3), with the $C_{p,>0.58\mu m}/C_{p,tot}$ for speaking with no mask is only ~0.15 on average (Fig. S4). The median large particle emission rate with no masks (NM) was $\dot{N}_{p,>0.58\mu m}$ = 1.8 particles/s (corresponding to $C_{p,>0.58\mu m}$ = 0.11 p/cm^3), consistent with previous observations[6,20] (Fig. 6). The observed particle size distribution from speaking shows that most particles emitted have diameters <7 µm, and with the particle concentration generally decreasing with diameter.

3.3.2 Cloth masks: For the cloth masks (Fig. 6a), particle emission rates with two of the masks (TC and TC-P) differed negligibly from the no mask case. Wearing of three of the cloth masks (LAP, COL, and TC-A) led to a notable decrease in the $\dot{N}_{p,>0.58\mu m}$, while the $\dot{N}_{p,>0.58\mu m}$ with wearing of two (HB and HW) led to a stark increase compared to the no mask emission rate on average. The Hanes Black (HB) and HW masks, with the higher-than-no-mask emission rates, are both 100% cotton, and both exhibited large emissions during rubbing. In contrast, all of the other cloth masks are polyester blends and exhibited comparably smaller emissions during rubbing.

The LAP, Columbia cloth masks (COL), and Tommie Copper cloth masks (TC) masks are all polyester (or blends). Wearing of two of these, LAP and COL, led to a notable reduction in the particle emissions ($R_{mask,>0.58\mu m}$ = 0.33 and 0.25, respectively) while only a moderate reduction was observed with the TC ($R_{mask,>0.58\mu m}$ = 0.77). The LAP was a single layer of relatively thick polyester and the mask fit fairly snugly around the nose despite not having a nose wire. The COL had two layers and the TC three layers. Qualitatively, there was no major difference in the fit of these masks as judged by the participant. It may be that the inner lining of the TC mask, which contained 35% cotton, contributed non-respiratory particles that led to an increased $\dot{N}_p$. However, the particle emissions during rubbing were no higher for the TC than for the COL or LAP masks (Fig. 6a). It may be that the inherent filtration efficiency of the TC was lower than for the other non-cotton cloth masks.

The insertion of the additional filters into the Tommie Copper cloth masks(TC) mask led to a decrease in the $\dot{N}_p$ in one case (the TC-A, with $R_{mask,>0.58\mu m}$ decreasing from 0.77 to 0.3) and a slight increase in the other case (the TC-P, with $R_{mask,>0.58\mu m}$ increasing from 0.77 to 0.85). The most noteworthy differences between the A and P filters are that (i) the former is larger (15 cm x 8.6 cm) than the latter (11 cm x 7.5 cm), and (ii) the A filter has two layers while the P filter has five layers. It may be that the thicker P filter provides greater resistance to flow than the A filter, which could lead to increased leakage out the mask side with the addition of the P filter. In contrast, air might pass through the thinner A filter more readily, leading to a decrease in the observed particle emission rate relative to no added filter. Our results indicate that the addition of an extra filter layer may not improve—and could potentially worsen by enhancing leakage—the net filtration of exhaled respiratory particles.

3.3.3 Bandana and Neck Gaiters: We also characterized a bandana (BAN) and two neck gaiters (BUF, TUR). The median large particle emission rate for bandana (BAN) was $\dot{N}_{p,>0.58\mu m}$ = 8.0 particles/s (corresponding to $C_{p,>0.58\mu m}$ = 0.48 p/cm^3), which is 320% higher (Fig. 6g) compared to wearing no mask. Rubbing and clean air flowing also show that bandana (BAN) has a similar performance as the HB and HW cloth masks. All three of these face coverings are 100% cotton, indicating that the excess particles resulted from the shedding of non-respiratory particles. During the speaking activity, even though the bandana (BAN) covered the participant's mouth and nose, the bottom of the bandana (BAN) had no sealing, and it exceeded the sampling funnel diameter. This likely led to some loss of respiratory particle emissions for BAN. Nonetheless, the observed particle emission rate for wearing the bandana (BAN) greatly exceeded that for no masks. The observed size distributions with wearing of the three 100% cotton-made face coverings (HB, HW, bandana (BAN)) all indicated an excess of smaller particles relative to no mask, along with a characteristic larger particle mode (at > 3 microns) relative to the no masks reference.

The median large particle emission rate for Buff neck gaiters (BUF) was $\dot{N}_{p,>0.58\mu m}$ = 5.5 particles/s (corresponding to $C_{p,>0.58\mu m}$ = 0.33 p/cm^3) and for TUR was $\dot{N}_{p,>0.58\mu m}$ = 7.0 particles/s (corresponding to $C_{p,>0.58\mu m}$ = 0.42 p/cm^3), 190% and 270% greater than $\dot{N}_{p,>0.58\mu m}$, respectively, compared to no mask wearing (Fig. 6g). The $C_{p,>0.58\mu m}/C_{p,tot}$ ratio for speaking with Buff neck gaiters (BUF) and TUR are only 3% and 5%, respectively, indicating the majority of excess particles were < 0.58 μm. A similar pattern appears in the APS size distribution (Fig. 7a), with most of the excess particles from BUF and Turtle Fur neck gaiters (TUR) < 2 microns.

Notably, the $\dot{N}_{p,tot}$ during speaking for the Buff neck gaiters (BUF) and Turtle Fur neck gaiters (TUR) were 205% and 150% higher than bandana (BAN) (Fig. S3d), indicating Buff neck gaiters (BUF) and bandana (BAN) emitted more small particles (<0.58μm) than bandana (BAN) because they all generated similar number of large particles (>0.58 μm) (Fig. 6i).

Qualitatively, during speaking, the participant noticed that Buff neck gaiters (BUF) and Turtle Fur neck gaiters (TUR) fit much better on the nose, mouth, and chin than bandana (BAN). The snug fit could have led to greater friction between the face covering and skin leading to greater shedding of skin particles (<0.58μm) and additional mask fibers (>0.58 μm). Certainly, shedding of skin particles could serve to increase any of the observed particle emission rates for any of the masks and would not be specific to the gaiters. In fact, the enhancement of the particles <1 micron relative to no mask for the HB and HW cloth masks (Fig. 7a) could indicate notable skin shedding for these masks as well. From our measurements it is not possible to quantitatively distinguish the contributions of mask material versus skin shedding to the observed particle emission rates. That wearing of some cloth masks led to a reduction in the observed particle emissions indicates that skin shedding does not occur to a substantial extent. It could be that different masks—owing to the material or the fit or both—have differing propensities to engender skin shedding during wearing. Single particle chemical analysis could help resolve this issue but was not possible here because we only had APS and MCPC for particle characterization.

3.3.4 Respirators: Figure 4c shows the $\dot{N}_{p,>0.58\mu m}$ for respirators. The KN95 and N95 respirators have the lowest $\dot{N}_{p,>0.58\mu m}$ of all the masks, averaging 0.09 p/s for the KN95 and 0.07, 0.1, and 0.18 for the T92, T85V, and ALG N95s, respectively, meaning they have the highest particle reduction efficiency. This results from their high material filtration efficiency and their generally tight fit[9,12]. Interestingly, although T85V has an exhalation valve, it has a similar $\dot{N}_p$ to the other respirators (Table 2), consistent with previous findings for this particular valved N95 model[26]. (We note that this may not be the case for all valved N95s or for all respiratory activities, as the performance of the valved N95s will depend importantly on how readily the valve opens during exhalation.[26,27]) The $\dot{N}_{p>0.58\mu m}$ with wearing the ALG is significantly higher than the other respirators (Table 2), albeit still very low.

3.3.5 Surgical Masks: With standard wearing the three surgical masks (Black surgical masks(SB), Fitty(FY), ChaX surgical masks(CX)) provide 80% particle reduction, on average, for large particles (Fig 6e). (Standard wearing means placing the ear strips directly behind the ear without crossing and ensuring the nose, mouth, and chin are well covered, then pinching the nose wire to seal the top side of the masks). Specifically, the median large particle emission rate for SB, FY, and CX were 3.5 p/s, 2.8 p/s, and 4.5 p/s. The $C_{p,>0.58\mu m}/C_{p,tot}$ ratio for all three surgical masks were under 20% (Fig. 6e), indicating most of the emitted particles were <0.58 µm. The small particle portion decreased from 99% to 80%, meaning more respiratory particles (>0.58 µm) were emitted(Fig. S4).

The three surgical masks were also tested when worn with the ear loops crossed (SBc, FYc, CXc). No difference in particle emissions was observed with ear loop crossing relative to standard wearing (p = 0.5, 0.09, 0.8). This indicates that crossing the ear loops neither enhanced nor reduced the particle emission compared to standard wearing, at least for the one participant. Qualitatively, the participant noticed that the surgical masks fit more tightly on the top and bottom when worn with the ear loops crossed. In contrast, the left and right sides fit more loosely against the participant's face because the mask's upper and lower corners are pulled in opposite directions. These factors could have canceled each other out, leading to a negligible overall change in the particle reduction efficiency.

3.3.6 Double Masking: Double masking, with a surgical mask inside and a cloth mask outside, has been recommended to improve the fit and filtration efficiency[12]. We assessed two combinations: SB-TC (surgical black mask inside and Tommie Copper cloth mask outside) and SB-HB (Surgical black mask inside and Hanes Black cloth mask outside). The large particle emission rate from speaking with the SB-TC averaged $\dot{N}_{p,>0.58\mu m}$ = 0.22 p/s (corresponding to $C_{p,>0.58\mu m}$ = 0.013 p/cm^3) while the SB-HB averaged $\dot{N}_{p,>0.58\mu m}$ = 0.33 p/s (corresponding to $C_{p,>0.58\mu m}$ = 0.02 p/cm^3), 90% and 84% lower N_p compared to no masks (Fig 4h). Double masking reduced the exhalation particle emission substantially compared to no mask wearing ($\dot{N}_{p,median}$ = 1.8 p/s) and compared to the SB ($\dot{N}_{p,median}$ = 0.5 p/s), TC ($\dot{N}_{p,median}$ = 1.6 p/s), and HB ($\dot{N}_{p,median}$ = 7.7 p/s) when worn individually. During the speaking experiment, the participant qualitatively felt that double masking led to an overall better fit than wearing single cloth and surgical masks. Even though the friction between the inner surgical mask would have likely increased, the non-respiratory particle emission did not increase, most likely because of the low propensity of the surgical mask to emit particles from friction. Correspondingly, the inner surgical mask likely reduced the friction between the cloth mask and the participant's face, leading to reduced non-respiratory emission from the cloth mask, while also increasing the overall filtration efficiency through the mask. The overall combination of improved fit, higher filtration efficiency, and reduced non-respiratory particle emissions led to large observed reduction efficiencies.

4. Conclusion

We examined the particle emission rate and size distributions from speaking while wearing five types of face coverings, with multiple face coverings of each type, and with two types of added mask filter inserts. We also characterized the extent to which the various masks shed non-respiratory particles as a result of rubbing or flowing clean air through them, alongside the shedding of skin particles from rubbing. Our results indicate that the observable outward particle emissions depend on three factors: the general mask fit, the filtration efficiency of the mask material, and the propensity for shedding of non-respiratory particles—either from the masks or from friction against the skin. This is observed both in terms of the absolute amount and the and size distribution of the emitted particles.

In general, the observed particle reduction during speaking was greatest for wearing of respirators and surgical masks, and these masks also showed a low propensity to shed non-respiratory particles. The three cotton masks (two cloth masks and a bandana) emitted the greatest number of particles upon rubbing, more than two orders of magnitude greater than the surgical masks or respirators. The particle emission during speaking with these same masks all increased relative to no mask wearing, almost certainly a result of shedding of non-respiratory particles during use. Shedding of these non-respiratory particles confounds determination of the effectiveness with which such masks reduce emitted respiratory particles. In addition, the emission of shed particles from the masks can potentially contribute to infectious disease transmission via aerosolized fomites[26]. Exposure to high levels of cotton dust has also been implicated as a contributing factor to respiratory disease for those working in the textile industry[28–30]. However, the particle concentrations observed here (<1 p/cm^3, or approximately 1 μg/m^3) are at least two orders of magnitude lower than exposures for textile workers[31] and the particle issues of cotton dust exposure may be related to the presence of particular endotoxins on raw cotton dust. As such, exposure to shed cotton fibers from masks is unlikely to present the same health concerns. Nonetheless, the infected individuals could contaminate their own mask and the aerosolized fomite from the face covering is a potential disease spreading route.

The particle emissions during speaking while wearing of the non-cotton (e.g., polyester) cloth masks were all reduced relative to no mask wearing, with two leading to substantial reduction (~70%) but the other only a moderate reduction (~20%) for large particles. For these masks there was limited evidence of notable emission of large non-respiratory particles, although we cannot rule out the possibility that such emissions led to an underestimate of the mask efficiency towards respiratory particles. The observed particle emissions during speaking while wearing the two neck gaiters exceeded that observed with no mask wearing, both for large particles and, especially, for smaller particles. The increased emissions likely resulted from shedding of non-respiratory fibers from the mask and of skin particles from rubbing of the masks against the face. We cannot rule out the possibility that shattering of larger droplets, producing smaller particles, occurred, as has been previously suggested[32]. However, we find shedding of fibers and skin particles a more plausible explanation in light of the rubbing experiment results, given that no evidence of droplet shattering was observed for the surgical masks and respirators, and based on unpublished results from "fake speaking" tests with a gaiter[33].

We also examined the influence of different wearing styles for surgical masks, specifically as typical or with crossed ear loops. We observed no difference in the particle emissions between these two styles, generally consistent with fit factors determined for inhalation and source control tests using manikins[34]. Other modifications, including knotting the ear loops with tucking the mask edges or using a brace to enhance the mask fit, did lead to increased fit factors or decreased source emission[13,29], but these modifications were not measured here. We did find that double masking, that is wearing a cloth mask over a surgical mask, increased the overall effectiveness of the masks at reducing respiratory particle emissions, consistent with previous fit factor or manikin-based source control tests[34].

Overall, our study complements measurements of material filtration efficiencies[9,35,36], fit factor inhalation tests[37,38], and manikin-based source control tests[8,39,40]. Our results demonstrate that shedding of mask fibers or skin particles can confound determination of mask source control efficiencies when worn by individuals, most notably for masks made of cotton but also for other mask types. As such, the observed efficiencies here, relative to no mask wearing, are likely underestimates of the actual efficiency for reducing respiratory particle emissions. Nonetheless, our results indicate that in terms of respiratory particle source control, respirators > surgical masks > cloth masks, consistent with current understanding. The potential for virus-contaminated shed mask fibers or skin particles to contribute to disease transmission requires further investigation. In other words, the correlation between the observed particle number and viral load is still not clear.

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Table 1. face coverings information.

Types	Manufacturer /model number	Acronym	Fastener	Nose wire	Material	Product
Reusable Cloth Masks	Hanes Masks (black)	HB	Ear loops	Yes	100% Cotton	3-ply
	Tultex (white)	HW	Ear loops	No	100% Cotton	3-ply
	LAPCOS	LAP	Ear loops	No	100% Polyester	1-ply
	Columbia	COL	Ear loops	Yes	Shell: 94% polyester 6% elastane. Lining: 100% polyester	2-ply
	Tommie Copper	TC	Ear loops	Yes	Shell: 85% Polyester, 15% elastane. Lining: 65% Polyester, 35% Cotton.	3-ply
Surgical masks	ChaX (tea mask)	CX	Ear loops	Yes	Shell: Polypropylene spun-bonded non-woven fabric. Lining: Polypropylene melt-blown non-woven fabric	3-ply
	NNPCBT (black)	SB	Ear loops	Yes	Surface: non-woven non-latex fabric. Middle layer: Polypropylene	3-ply
	Fitty	FY	Ear loops	Yes	Surface: non-woven non-latex fabric. Middle layer: Polypropylene	3-ply
Respirators	Hotodeal KN95 Model number: KN95 (PM 2.5) Protective Mask	KN	Ear loops	Yes	2 non-woven outer layers, 2 melt-blown inner filter, 1 non-woven cotton	5-ply
	3M 9205P-3-DC Aura Particulate Respirator	T92	Headbands	Yes	polypropylene and coverings typically made from a combination of polypropylene, polyester	\
	ALG Health Patriot N95 Mask Model number: PT-N95CS-06	ALG	Headbands	Yes	Material: cotton. Fabric type: melt-blown, non-woven electrostatic filtration fabric	\
	3M 8511(3M cool flow valve)	T85V	Headbands	Yes	polyester, polypropylene, polyisoprene	M-nose clip
Bandana	Levis	BAN	Ties behind head	No	100% cotton	2-ply
Neck gaiters	Buff (CoolNet UV)	BUF	Encircles head	No	95% polyester, 5% elastane	1-ply
	The Turtle Fur	TUR	Encircles head	No	100% spun acrylic fleece	1-ply
Mask filters	Airflow Product ASIN: B086D4MLBY	TC-A	N/A	N/A	100% electrostatically charged melt-down polypropylene	1 thick layer
	JCBABA	TC-P	N/A	N/A	Material: 2*Anti-sticking cloth, 1 *Filter cloth, 1 * Activated Carbon and 1 * Efficient filter cloth	5 layers

Table 2. P-values of every pair of face covering from single-factor ANOVA test. Colors indicate the magnitude of p-values, from light yellow ($p < 0.001$), to dark blue ($p > 0.15$), which illustrates the statistical significance of the difference between particle emission rates.

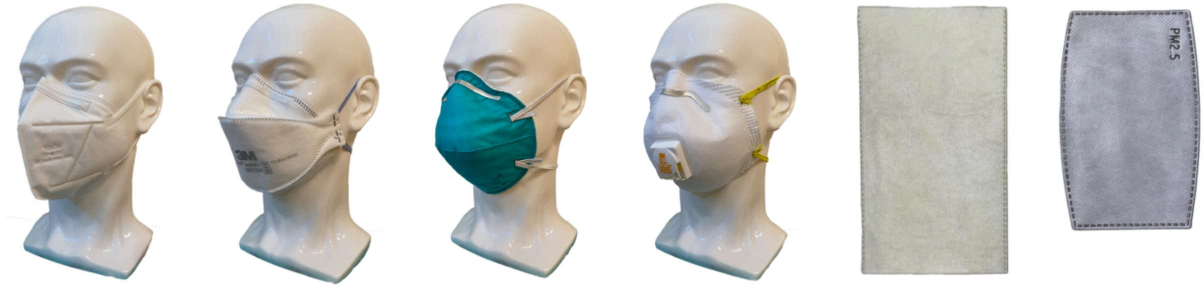
		No masks	Cloth masks							Respirators				Neck gaiters and bandana			Surgical masks						Double masks			
		NM	HB	HW	LAP	COL	TC	TC-A	TC-P	KN	T92	T85V	ALG	BUF	TUR	BAN	SB	SBc	FY	FYc	CX	CXc	SB-HB	SB-TC		
No masks	NM		8.24E-04	6.35E-03	3.51E-03	6.05E-04	2.52E-01	9.05E-04	7.97E-01	1.24E-04	3.16E-05	3.96E-04	7.76E-04	5.75E-04	1.91E-03	9.29E-02	3.55E-04	1.61E-04	2.39E-05	1.59E-04	1.24E-04	2.01E-04	2.82E-04	1.41E-04	NM	No masks
Cloth masks	HB	8.24E-04		4.36E-01	8.69E-04	2.49E-04	4.11E-04	2.59E-04	3.96E-04	1.75E-04	5.47E-05	5.43E-04	6.32E-04	1.61E-01	6.90E-01	5.36E-01	8.76E-05	7.60E-05	2.18E-05	7.73E-05	7.52E-05	7.60E-05	2.07E-04	1.80E-04	HB	Cloth masks
	HW	6.35E-03	4.36E-01		9.09E-03	3.92E-03	4.40E-03	3.97E-03	3.38E-03	3.17E-03	1.43E-03	6.90E-03	7.55E-03	1.16E-01	3.39E-01	2.69E-01	1.88E-03	1.74E-03	7.50E-04	1.76E-03	1.74E-03	1.77E-03	3.49E-03	3.22E-03	HW	
	LAP	3.51E-03	8.69E-04	9.09E-03		7.78E-02	1.44E-02	3.03E-01	2.14E-02	1.56E-04	1.94E-05	2.05E-04	3.75E-03	1.50E-04	1.63E-03	6.62E-02	2.27E-01	3.43E-02	4.95E-04	2.33E-02	1.99E-03	6.58E-02	9.68E-03	2.81E-04	LAP	
	COL	6.05E-04	2.49E-04	3.92E-03	7.78E-02		2.42E-03	9.33E-01	5.50E-03	6.66E-04	6.72E-05	6.32E-04	4.83E-02	2.42E-03	9.33E-01	5.50E-03	8.82E-01	2.81E-01	6.16E-03	2.95E-01	7.98E-02	4.36E-01	8.54E-02	1.48E-03	COL	
	TC	2.52E-01	4.11E-04	4.40E-03	1.44E-02	2.42E-03		3.92E-03	4.61E-01	3.29E-04	8.71E-05	9.42E-04	2.20E-03	1.58E-04	9.21E-04	6.31E-02	1.79E-03	6.82E-04	9.13E-05	6.71E-04	4.88E-04	8.93E-04	9.25E-04	3.85E-04	TC	
	TC-A	9.05E-04	2.59E-04	3.97E-03	3.03E-01	9.33E-01	3.92E-03		6.71E-03	2.56E-02	7.12E-03	4.30E-02	2.73E-01	3.45E-05	5.12E-04	3.86E-02	8.53E-01	3.87E-01	5.05E-02	4.34E-01	3.21E-01	5.09E-01	2.16E-01	3.70E-02	TC-A	
	TC-P	7.97E-01	3.96E-04	3.38E-03	2.14E-02	5.50E-03	4.61E-01	6.71E-03		1.32E-03	4.51E-04	3.22E-03	5.93E-03	3.87E-04	1.04E-03	6.62E-02	3.22E-03	1.77E-03	4.02E-04	1.86E-03	1.62E-03	2.09E-03	2.63E-03	1.47E-03	TC-P	
Respirators	KN	1.24E-04	1.75E-04	3.17E-03	1.56E-04	6.66E-04	3.29E-04	2.56E-02	1.32E-03		3.55E-01	7.14E-01	1.04E-02	1.73E-05	3.41E-04	2.98E-02	4.14E-02	7.00E-02	3.01E-01	1.96E-02	8.12E-04	5.93E-02	1.27E-01	6.96E-01	KN	Respirators
	T92	3.16E-05	5.47E-05	1.43E-03	1.94E-05	6.72E-05	8.71E-05	7.12E-03	4.51E-04	3.55E-01		1.36E-01	9.06E-04	4.03E-06	1.10E-04	1.79E-02	1.24E-02	1.80E-02	6.87E-02	3.27E-03	4.11E-05	1.60E-02	3.15E-02	1.99E-01	T92	
	T85V	3.96E-04	5.43E-04	6.90E-03	2.05E-04	6.32E-04	9.42E-04	4.30E-02	3.22E-03	7.14E-01	1.36E-01		2.65E-03	6.98E-05	1.01E-03	4.83E-02	6.81E-02	1.07E-01	4.15E-01	3.03E-02	1.72E-04	9.29E-02	1.75E-01	9.05E-01	T85	
	ALG	7.76E-04	6.32E-04	7.55E-03	3.75E-03	4.83E-02	2.20E-03	2.73E-01	5.93E-03	1.04E-02	9.06E-04	2.65E-03		8.88E-05	1.18E-03	5.36E-02	3.87E-01	7.97E-01	1.86E-01	5.63E-01	3.49E-01	6.42E-01	7.51E-01	2.85E-02	ALG	
Neck gaiters and bandana	BUF	5.75E-04	1.61E-01	1.16E-01	1.50E-04	2.42E-03	1.58E-04	3.45E-05	3.87E-04	1.73E-05	4.03E-06	6.98E-05	8.88E-05		3.36E-01	8.30E-01	9.33E-06	7.11E-06	1.39E-06	7.13E-06	6.60E-06	7.66E-06	2.30E-05	1.81E-05	BUF	Neck gaiters and bandana
	TUR	1.91E-03	6.90E-01	3.39E-01	1.63E-03	9.33E-01	9.21E-04	5.12E-04	1.04E-03	3.41E-04	1.10E-04	1.01E-03	1.18E-03	3.36E-01		7.51E-01	1.81E-04	1.56E-04	4.58E-05	1.58E-04	1.53E-04	1.62E-04	4.05E-04	3.50E-04	TUR	
	BAN	9.29E-02	5.36E-01	2.69E-01	6.62E-02	5.50E-03	6.31E-02	3.86E-02	6.62E-02	2.98E-02	1.79E-02	4.83E-02	5.36E-02	8.30E-01	7.51E-01		2.45E-02	2.24E-02	1.27E-02	2.28E-02	0.0225266	2.30E-02	3.33E-02	3.04E-02	BAN	
Surgical masks	SB	3.55E-04	8.76E-05	1.88E-03	2.27E-01	8.82E-01	1.79E-03	8.53E-01	3.22E-03	4.14E-02	1.24E-02	6.81E-02	3.87E-01	9.33E-06	1.81E-04	2.45E-02		5.04E-01	8.22E-02	5.79E-01	6.41E-01	4.76E-01	2.98E-01	5.90E-02	SB	Surgical masks
	SBc	1.61E-04	7.60E-05	1.74E-03	3.43E-02	2.81E-01	6.82E-04	3.87E-01	1.77E-03	7.00E-02	1.80E-02	1.07E-01	7.97E-01	7.11E-06	1.56E-04	2.24E-02	5.04E-01		2.12E-01	8.38E-01	8.95E-01	8.32E-01	6.32E-01	1.09E-01	SBc	
	FY	2.39E-05	2.18E-05	7.50E-04	4.95E-04	6.16E-03	9.13E-05	5.05E-02	4.02E-04	3.01E-01	6.87E-02	4.15E-01	1.86E-01	1.39E-06	4.58E-05	1.27E-02	8.22E-02	2.12E-01		9.49E-02	3.67E-02	1.58E-01	4.45E-01	4.90E-01	FY	
	FYc	1.59E-04	7.73E-05	1.76E-03	2.33E-02	2.95E-01	6.71E-04	4.34E-01	1.86E-03	1.96E-02	3.27E-03	3.03E-02	5.63E-01	7.13E-06	1.58E-04	2.28E-02	5.79E-01	8.38E-01	9.49E-02		8.85E-01	9.67E-01	4.46E-01	3.60E-02	FYc	
	CX	1.24E-04	7.52E-05	1.74E-03	1.99E-03	7.98E-02	4.88E-04	3.21E-01	1.62E-03	8.12E-04	4.11E-05	1.72E-04	3.49E-01	6.60E-06	1.53E-04	0.0225266	6.41E-01	8.95E-01	3.67E-02	8.85E-01		8.77E-01	3.77E-01	2.85E-03	CX	
	CXc	2.01E-04	7.60E-05	1.77E-03	6.58E-02	4.36E-01	8.93E-04	5.09E-01	2.09E-03	5.93E-02	1.60E-02	9.29E-02	6.42E-01	7.66E-06	1.62E-04	2.30E-02	4.76E-01	8.32E-01	1.58E-01	9.67E-01	8.77E-01		5.07E-01	8.99E-02	CXc	
Double masks	SB-HB	2.82E-04	2.07E-04	3.49E-03	9.68E-03	8.54E-02	9.25E-04	2.16E-01	2.63E-03	1.27E-01	3.15E-02	1.75E-01	7.51E-01	2.30E-05	4.05E-04	3.33E-02	2.98E-01	6.32E-01	4.45E-01	4.46E-01	3.77E-01	5.07E-01		2.05E-01	SB-HB	Double masks
	SB-TC	1.41E-04	1.80E-04	3.22E-03	2.81E-04	1.48E-03	3.85E-04	3.70E-02	1.47E-03	6.96E-01	1.99E-01	9.05E-01	2.85E-02	1.81E-05	3.50E-04	3.04E-02	5.90E-02	1.09E-01	4.90E-01	3.60E-02	2.85E-03	8.99E-02	2.05E-01		SB-TC	
		NM	HB	HW	LAP	COL	TC	TC-A	TC-P	KN	T92	T85	ALG	BUF	TUR	BAN	SB	SBc	FY	FYc	CX	CXc	SB-HB	SB-TC		
		No masks	Cloth masks							Respirators				Neck gaiters and bandana			Surgical masks						Double masks			

🟨	**$p < 0.001$**
🟨	**$0.001 < p < 0.01$**
🟨	**$0.01 < p < 0.05$**
🟦	**$0.05 < p < 0.15$**
🟦	**$0.15 < p$**

(a) Hanes Black (HB) **(b)** Tulex white (HW) **(c)** LAPCOS (LAP) **(d)** Columbia (COL) **(e)** Tommie Copper (TC)

(f) ChaX (CX) **(g)** ChaX_cross (CXc) **(h)** NNPCBT (SB) **(i)** NNPCBT_cross (SBc) **(j)** Fitty (FY) **(k)** Fitty_cross (FYc)

(l) KN95 (KN) **(m)** 3M 9205 (T92) **(n)** ALG N95 (ALG) **(o)** 3M 8511 (T85V) **(p)** filter 1 (A) **(q)** filter 2 (P)



(r) Bandana (BAN) **(s)** Neck gaiter 1 (BUF) **(t)** Neck gaiters 2 (TUR) **(u)** Double masks 1 (SB-TC) **(v)** Double masks 2 (SB-HB)

Figure 1. Images of the face coverings used for the experiments. Fig.1 is an illustration of a real person wearing face (c) covering. We investigated four types of face covering and various wearing styles, including (a)-(e) cloth masks, (f)-(k) surgical masks in regular and cross ear loop style, (l)-(o) KN95 and N95 respirators, (r)-(t) bandana and neck gaiters, (u)-(v) double masks with a cloth mask outside and a surgical mask inside. (p) and (q) are two types of masks filters, which can be inserted to the inner layer of the masks.

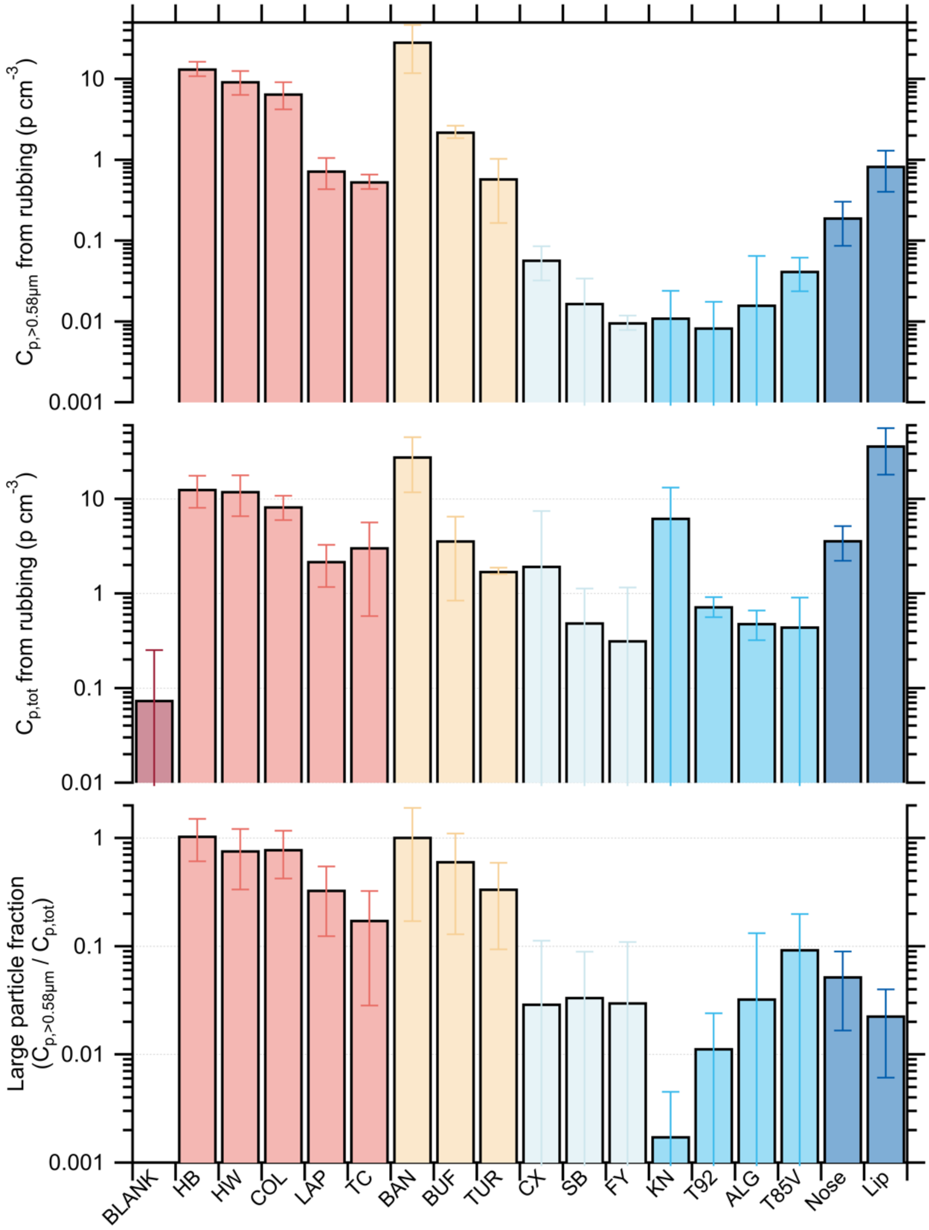


Figure 2. Rubbing experiment results: (a) the geometric average and standard deviation of the particle concentration ratio of the large particles for the background and all masks. (b) the geometric average and standard deviation of the overall particle concentration was measured by MCPC. (c) the geometric average and standard deviation of the large particle concentration measured by APS. The color difference represents the different types of face coverings: the red prink is associated with cloth masks; the dark yellow is associated with bandana and neck gaiters; the light blue is associated with surgical masks; the sky-blue is associated with respirators; the dark blue is associated with skin rubbing. The error bars are the one standard deviation.

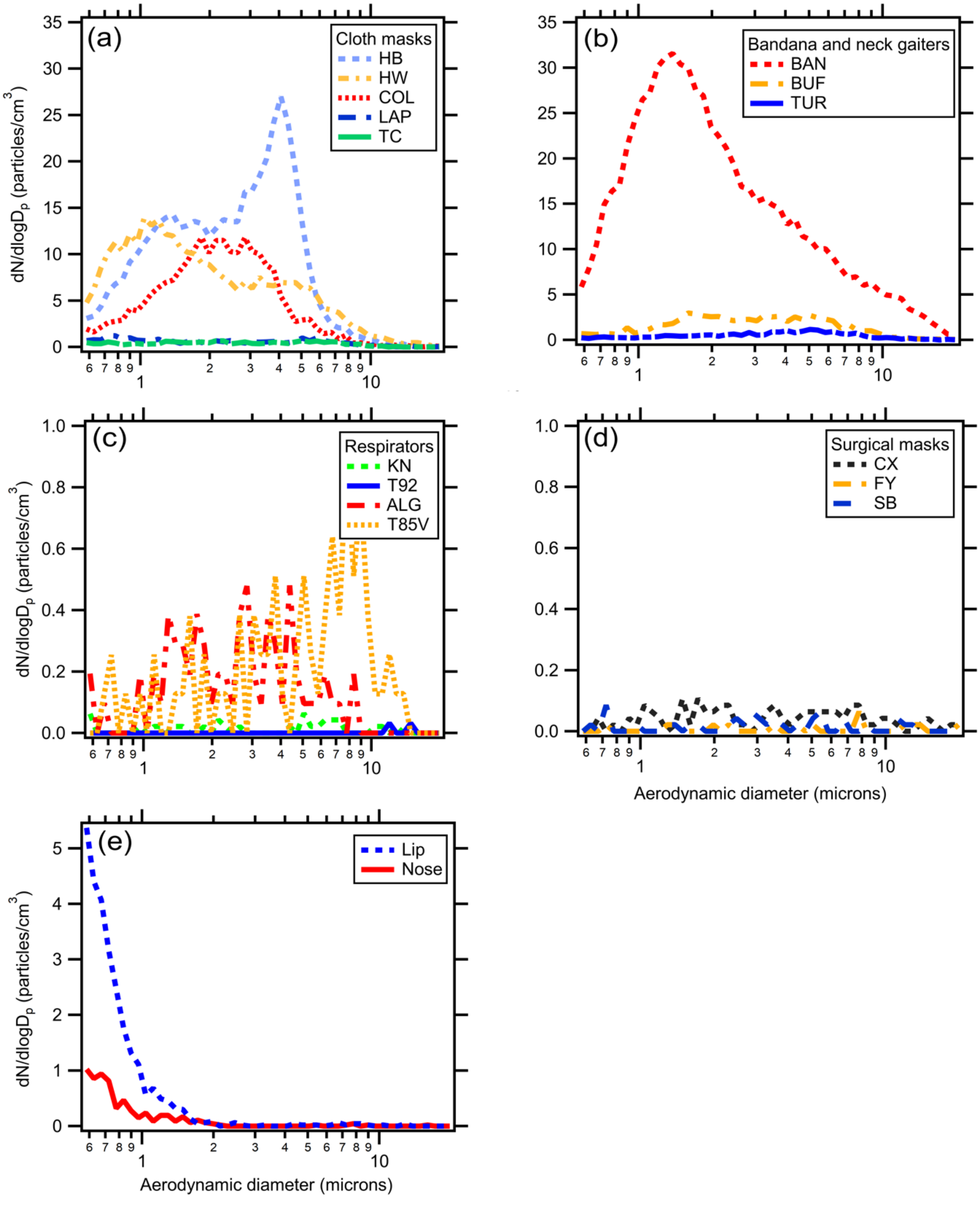


Figure 3. The size distribution from the rubbing experiment for (a) cloth masks, (b) the bandana and neck gaiters, (c) respirators, (d) surgical masks, and (e) rubbing against lip and nose using the SB surgical mask.

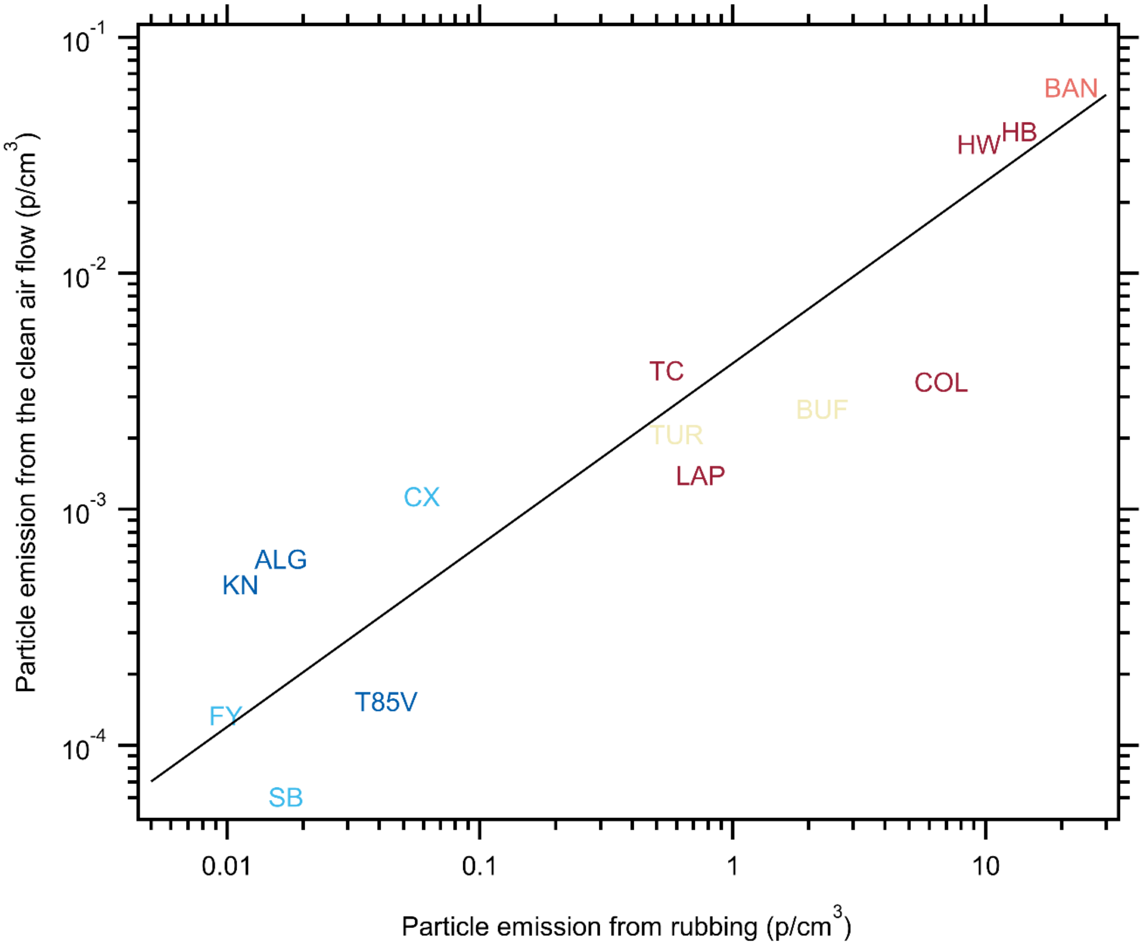


Figure 4. The averaged non-respiratory particle emission from clean airflow versus rubbing activities, with mask type indicated by the abbreviations. Note the difference in scales between the x and y axes. Solid black line is the linear fit with $R^2 = 0.935$.

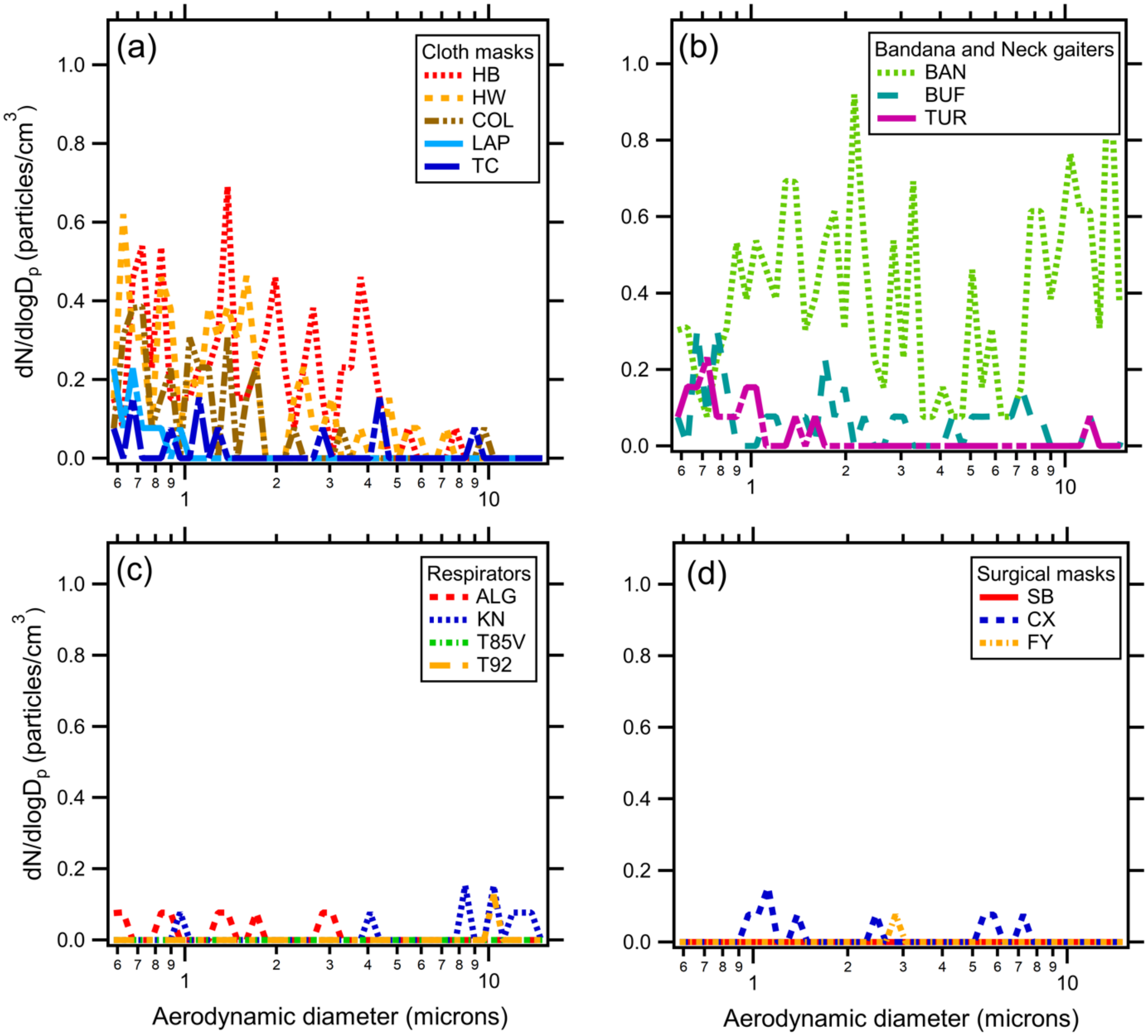


Figure 5. Averaged particle size distribution of flowing air through the masks activity, from (a) cloth masks, (b) bandana and neck gaiters, (c) respirators, (d) surgical masks, with labeled material name abbreviation.

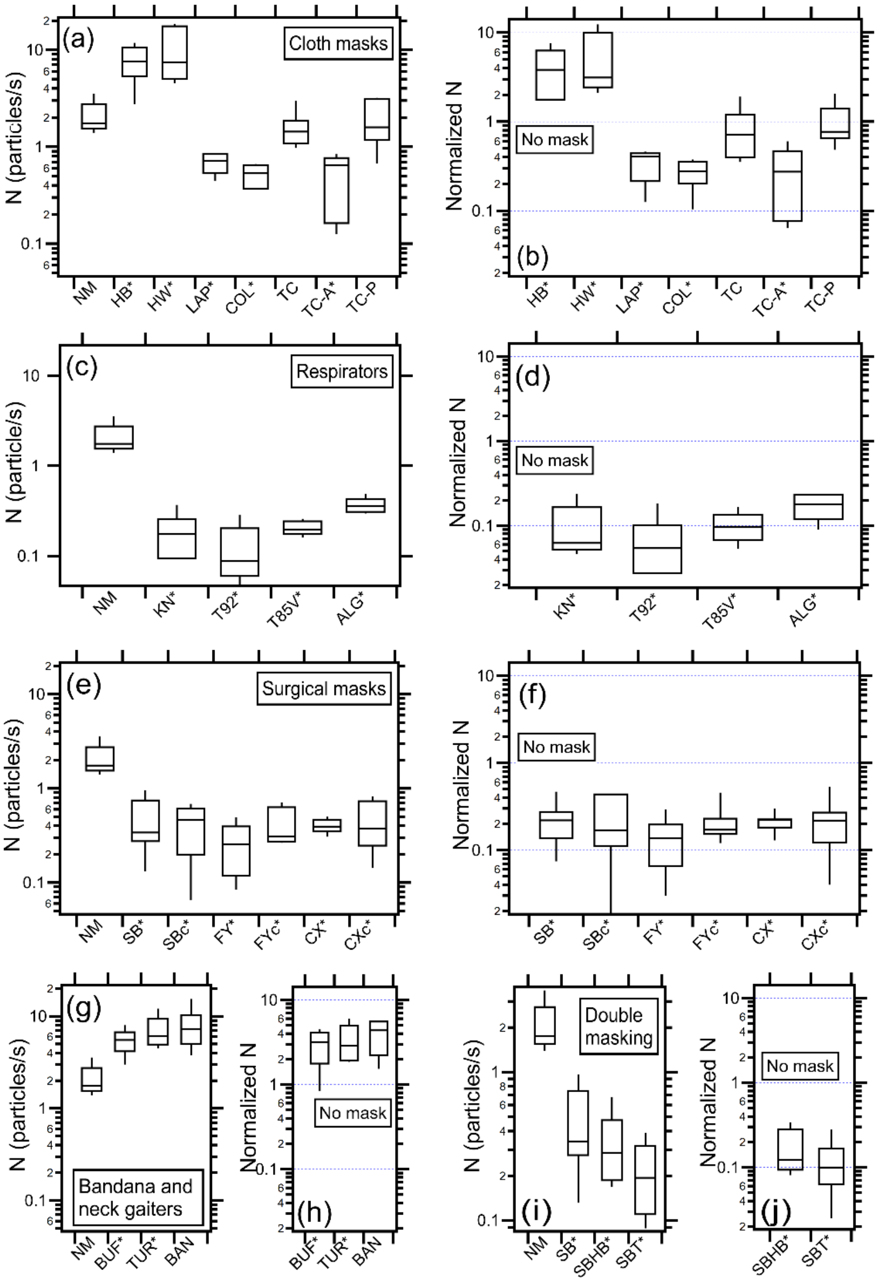


Figure 6. Measured large particle emission rate ($\dot{N}_{p,>0.58\mu m}$) for speaking activity, associated (a) cloth masks, (c) respirators, (e) surgical masks, (g) bandana and neck gaiters, and (i) double masking. Measured ratios between the particle emission rates with mask wearing to no mask wearing for (a) cloth masks, (c) respirators, (e) surgical masks, (g) bandana and neck gaiters, and (h) double masking. The asterisks are labeled with P values<0.05 comparing to no mask (NM), indicating the significant difference level between each mask and NM. The detailed P values are shown in table 2.

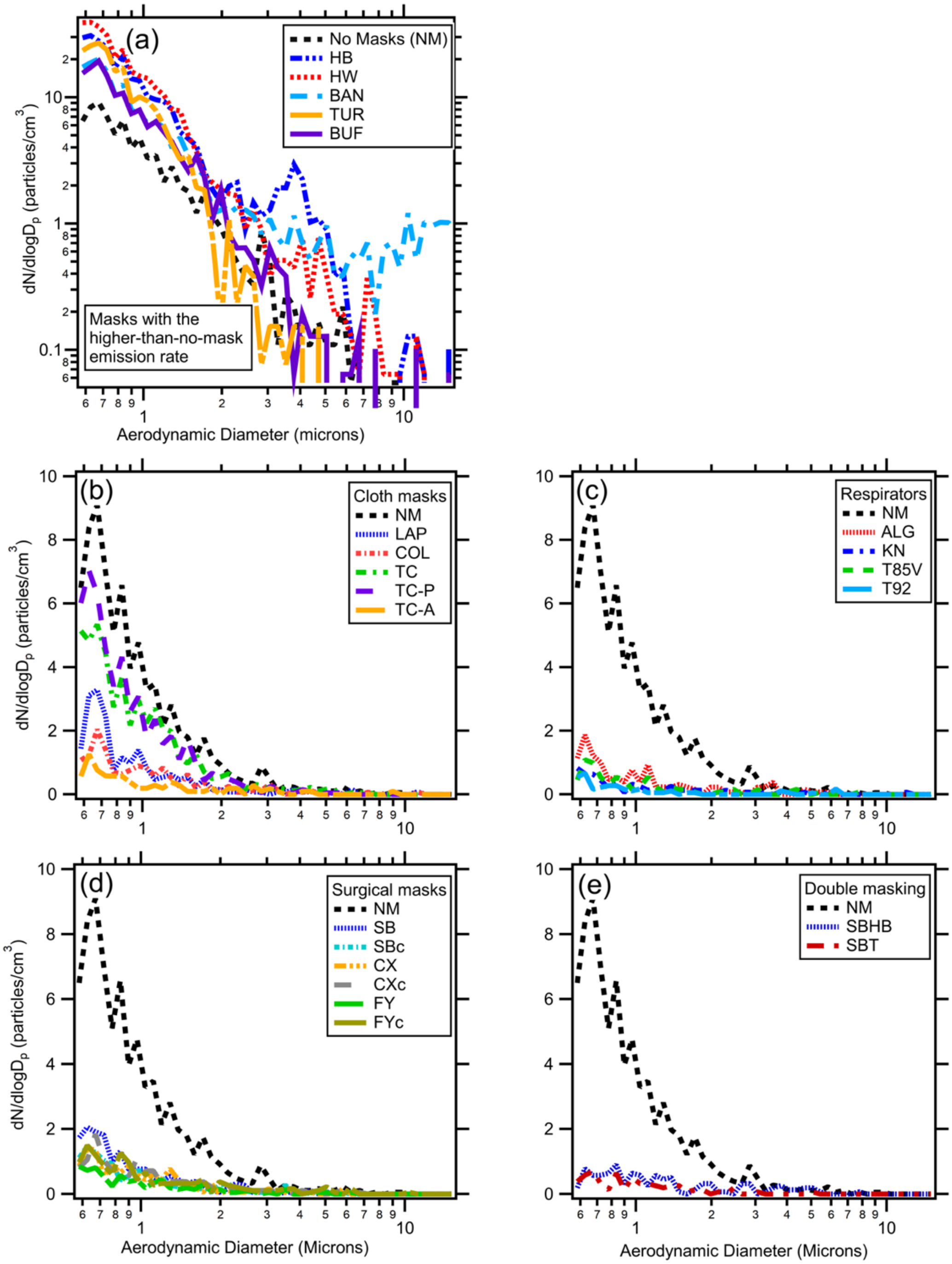


Figure 7. Averaged particle size distribution for speaking activity, from (a) face coverings that emitted higher number of particles than no masks, (b) the rest of cloth masks, (c) respirators, (d) surgical masks, (e) double masking, with labeled material abbreviation.

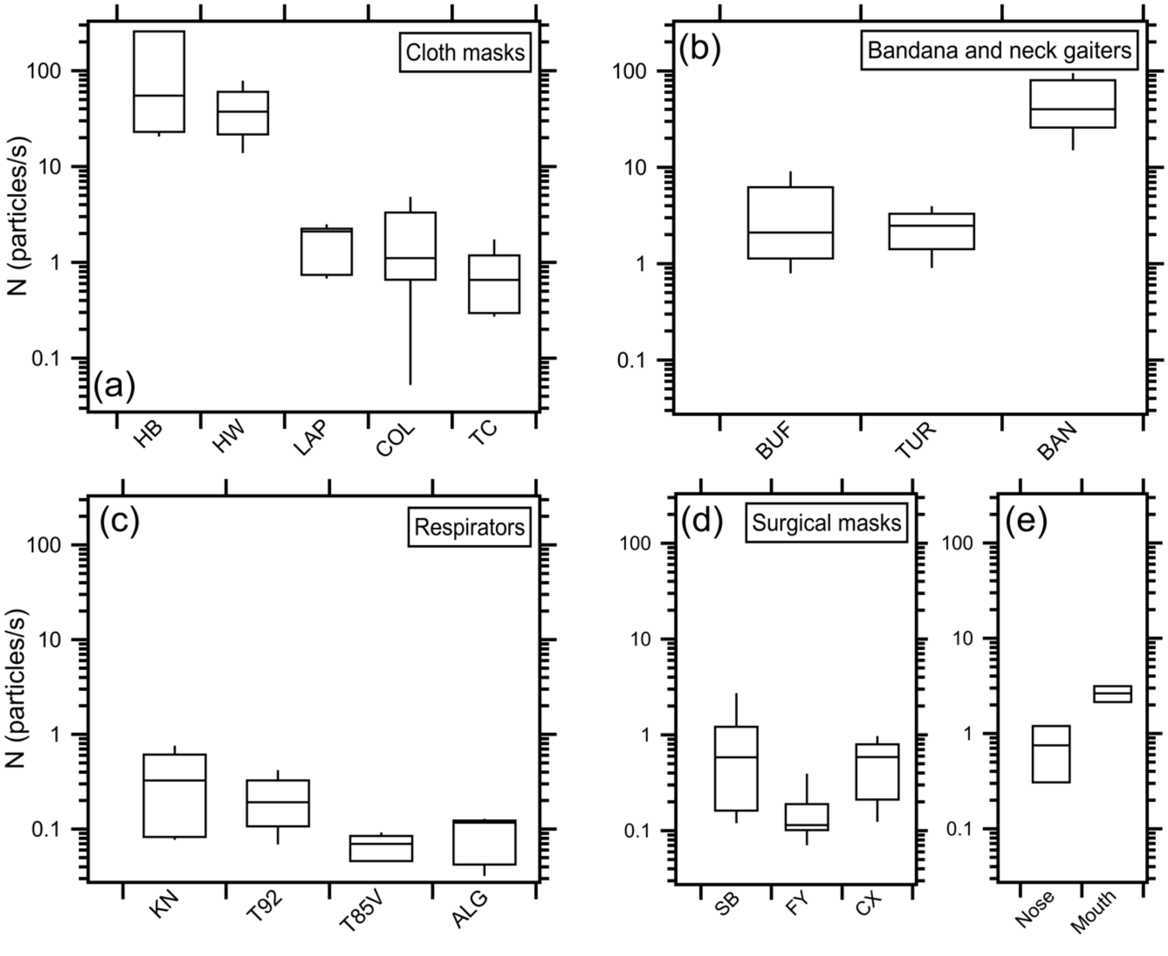


Figure 8. Measured particle emission from the manual rubbing activity, associated with (a) cloth masks, (b) bandana and neck gaiters, (c) respirators, (d) surgical masks, and (e) rubbing against nose and mouth.

Supplementary Text S1

“When the sunlight strikes raindrops in the air, they act as a prism and form a rainbow. The rainbow is a division of white light into many beautiful colors. These take the shape of a long round arch, with its path high above, and its two ends apparently beyond the horizon. There is, according to legend, a boiling pot of gold at one end. People look, but no one ever finds it. When a man looks for something beyond his reach, his friends say he is looking for the pot of gold at the end of the rainbow. Throughout the centuries people have explained the rainbow in various ways. Some have accepted it as a miracle without physical explanation. To the Hebrews it was a token that there would be no more universal floods. The Greeks used to imagine that it was a sign from the gods to foretell war or heavy rain. The Norsemen considered the rainbow as a bridge over which the gods passed from earth to their home in the sky. Others have tried to explain the phenomenon physically. Aristotle thought that the rainbow was caused by reflection of the sun's rays by the rain. Since then, physicists have found that it is not reflection, but refraction by the raindrops which causes the rainbows. Many complicated ideas about the rainbow have been formed. The difference in the rainbow depends considerably upon the size of the drops, and the width of the colored band increases as the size of the drops increases. The actual primary rainbow observed is said to be the effect of superimposition of a number of bows. If the red of the second bow falls upon the green of the first, the result is to give a bow with an abnormally wide yellow band, since red and green light when mixed form yellow. This is a very common type of bow, one showing mainly red and yellow, with little or no green or blue.”

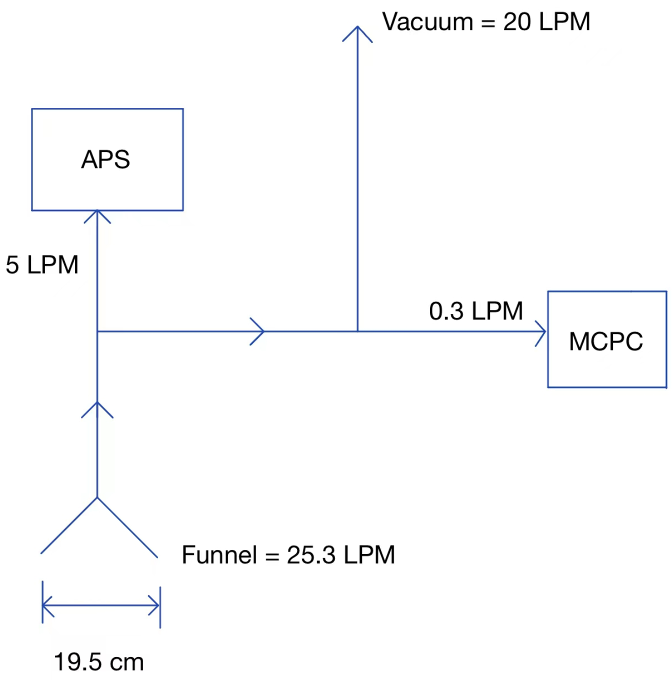


Figure S1. Experimental set up for particle emission measurement while speaking, mask rubbing, and flowing are through masks activities.

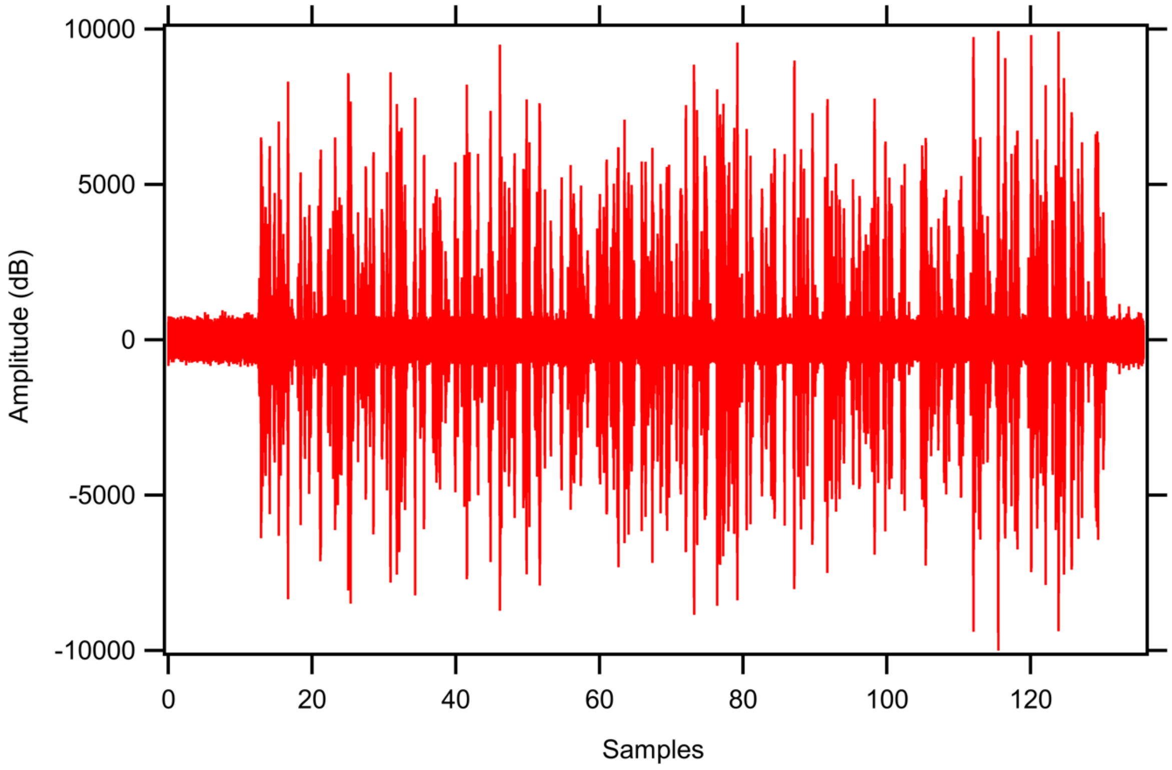


Figure S2. Audio recordings for an exemplary speaking activity.

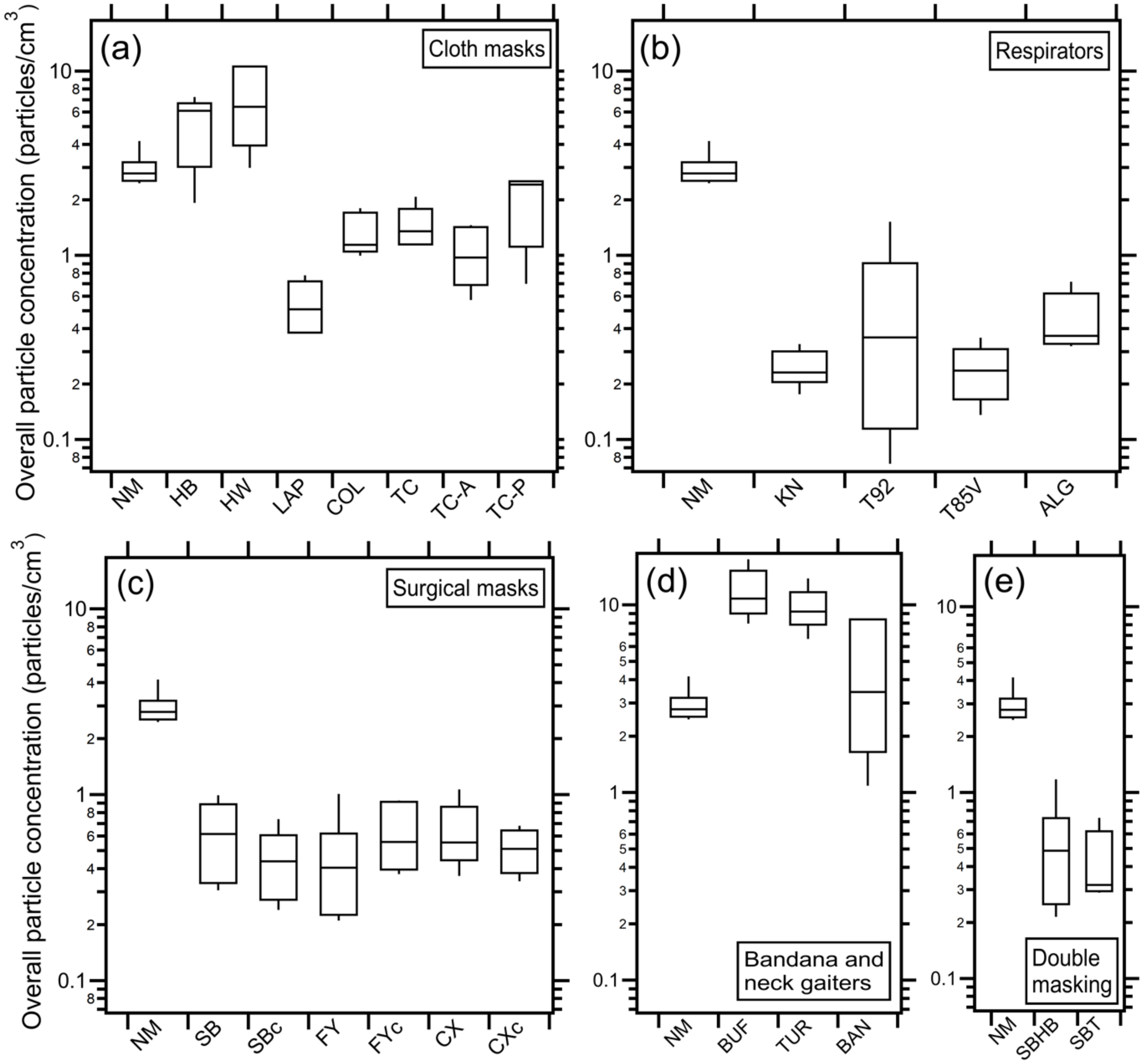


Figure S3. Total particle concentration for speaking activity measured by MCPC.

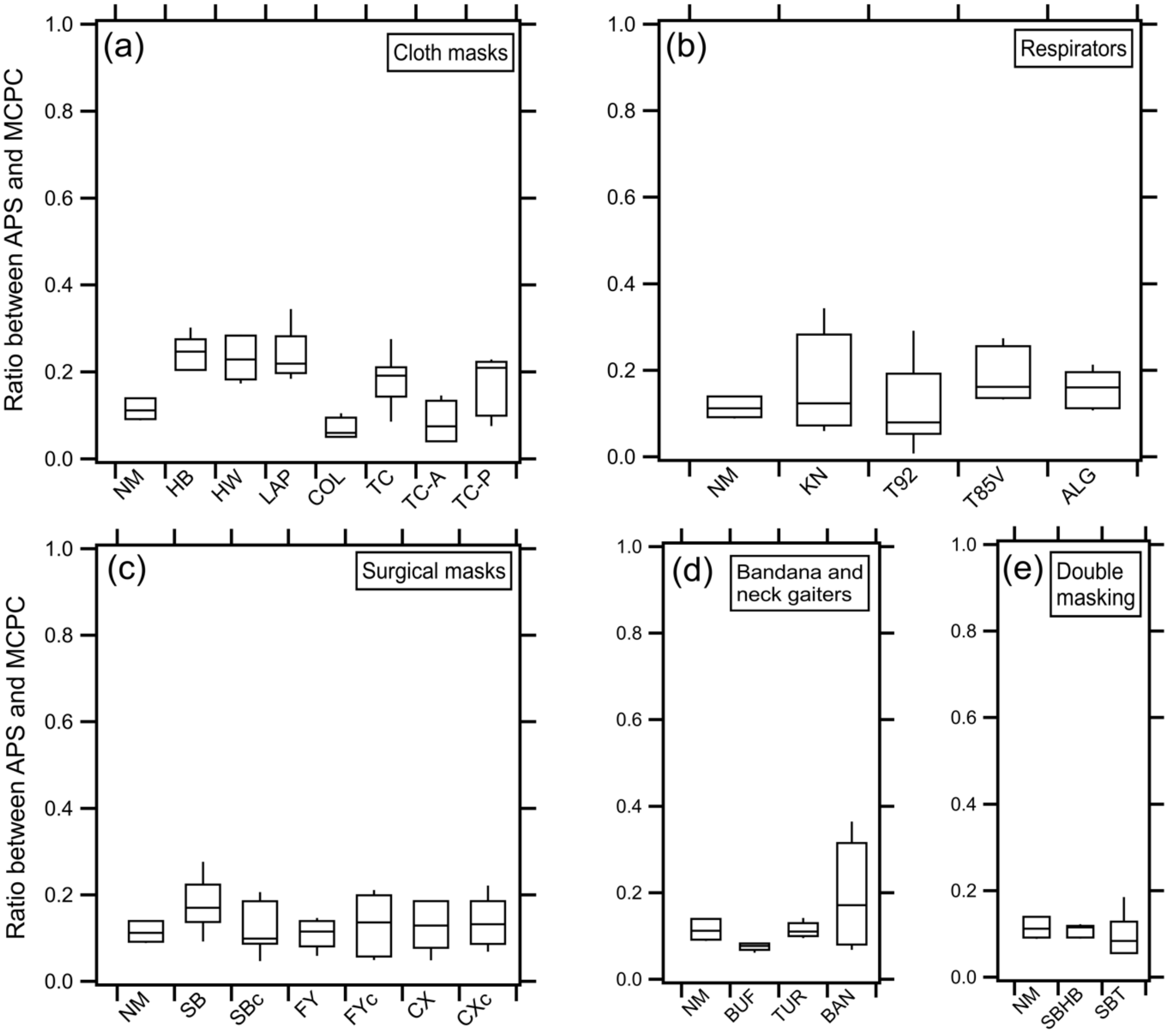


Figure S4. The ratio between the particle emission rate from speaking activity measured by APS (measured particles that >0.58μm) and the adjusted particle emission rate from MCPC (characterized all particles > 10 nm).

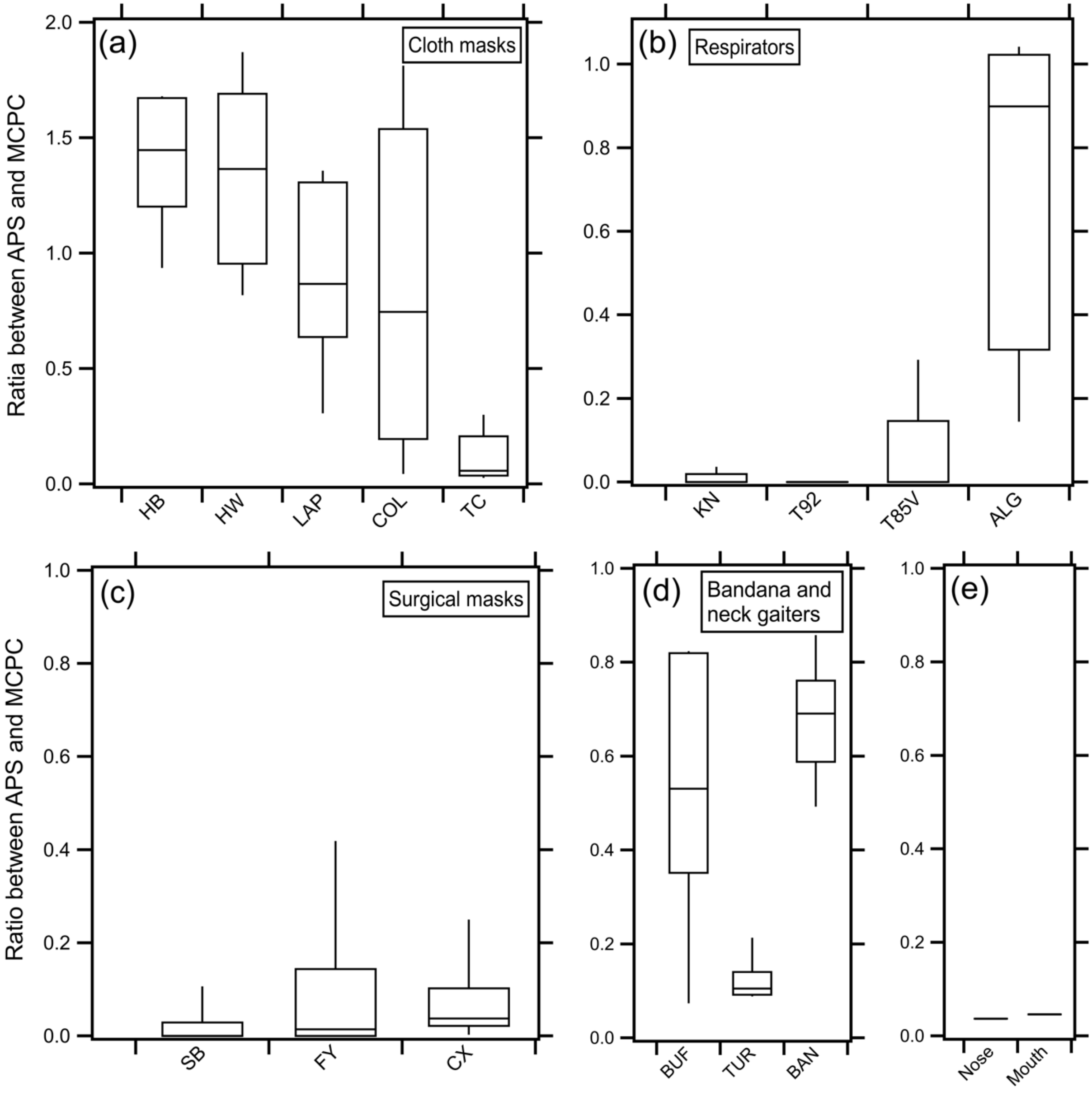


Figure S5. The ratio between the particle emission rate from rubbing activity measured by APS (measured particles that >0.58µm) and the MCPC (characterized all particles > 10 nm).