On the use of gaiters for mitigation of Covid-19 transmission during exercise

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Abstract:

In an indoor exercise environment, such as a weight room or other training facility, it is important to have face coverings to prevent the aerosol transmittance of SARS-CoV-2 virus. A popular choice for such a covering is an elastic neck gaiter which is pulled up over the mouth and nose. We demonstrate via laser sheet imaging that when dry such a gaiter is efficient in capturing the droplet emissions associated with speech. When wet, however, sharp exhalation such as would occur during exercise or the vocalization of the word "pop" leads to large scale atomization of droplets of O(40μm) diameter which would rapidly condense to aerosol nuclei. This atomization did not occur in testing of commercial exercise masks. Thus, the use of a gaiter in mouth covering for exercise should be avoided.

Introduction:

It has become clear in recent weeks that indoor environments such as bars, restaurants, gyms, or other gathering places are an important vector for transmission of the SARS-CoV-2 virus which leads to the Covid-19 pandemic. An early example of spreading associated with gyms, for example, is the spread associated with dance exercise classes in Cheonan, South Korea in February in which 112 individuals were infected (Jang, et al., DOI: https://doi.org/10.3201/eid2608.200633). In order to mitigate such transmission, athletes are now required in Indiana to maintain a minimum separation distance, clean equipment between each use to limit fomite transmission, and wear face coverings to prevent large droplet and aerosol transmission. Because exercise requires heavy breathing, it is important to have face coverings which do not unduly restrict air flow. This is, of course, difficult if aerosol and droplet mitigation is also to be achieved. A popular choice is the use of an elastic neck gaiter (single layer) which is pulled over the mouth and nose. In this paper we examine droplet production for such a gaiter, and demonstrate that while it is effective against droplets produced by vocalization when dry, sharp exhalation through the elastic material when wet produces a very large number of droplets, essentially converting the liquid on the gaiter to an aerosol.

Experiment:

In the course of planning for the reopening of the University of Notre Dame this fall, an experimental study of face coverings for use in the classroom was initiated. These experiments consisted of a laser sheet imaging experiment in which a test subject (DTL) would perform vocalizations directed toward the laser sheet and the images would be recorded for different face coverings. The laser sheet was produced using a 400mW green diode laser directed twice through a concave cylindrical lens and focused using a 145mm spherical lens. This sheet was directed horizontally by means of a 45 degree mirror. The imaging area was approximately 5cm high by 10cm long (laser propagation direction), well within the 8cm width of the sheet. Because of the relatively low power of the laser sheet, the camera (Sony DCR-PC110) was at an angle of 45°, capturing the scattered light in forward scatter mode. Based on the brightness of 50μm glass spheres scattered through the laser sheet, droplets above approximately 10μm in diameter could be readily imaged in the sheet. In testing, the subject would place the mouth approximately 7cm from the center of the laser sheet directing exhalations into the observation window at a 45 degree angle, perpendicular to the direction of the camera. To capture droplets which simply leaked from a mask without significant forward velocity, a fan fitted with a MERV 12 filter was placed behind the subject and directed at the laser sheet. The convective velocity of the fan was approximately 0.5m/s. The experimental setup is depicted in figure 1.

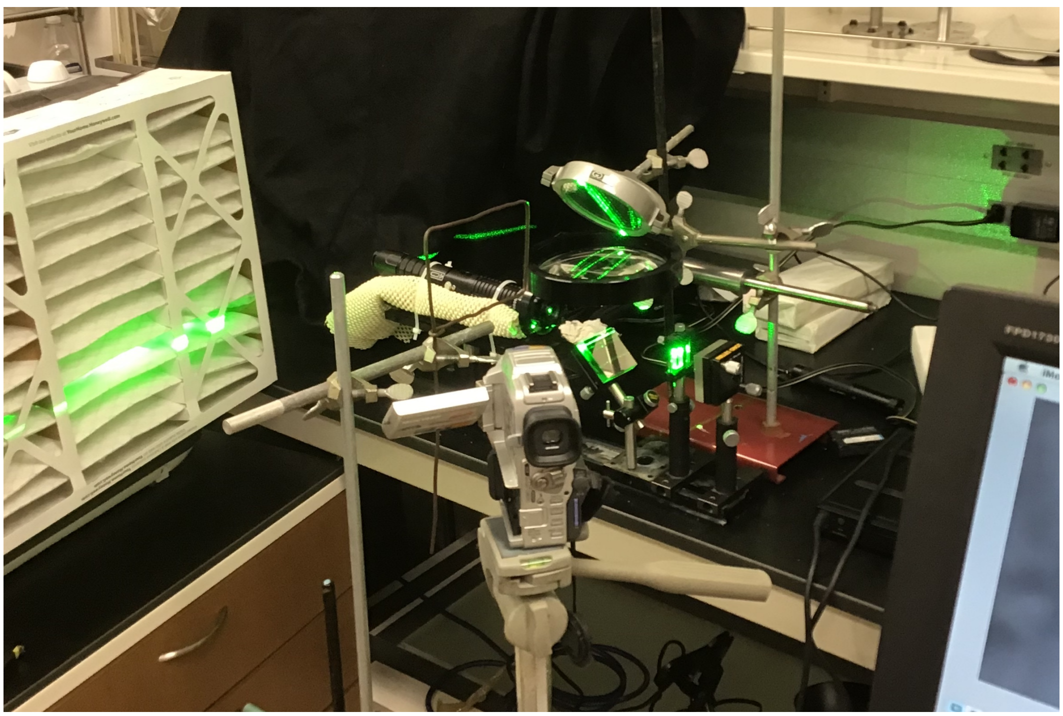

Figure 1. Laser sheet imaging system. The wire rectangle outlines the observation window of the sheet/camera system for orientation of the test subject located between the fan and the rectangle.

Images were directly recorded to a computer in iMovie, and then 20 second clips were exported to a sequence of jpegs for analysis in Matlab. The images were processed by converting to grayscale, subtracting off the average to remove background, and then enhanced using a point filter. Particles up to a set limit and threshold were identified and counted. The brightness of a particular particle was also recorded as that would be related to droplet size, although complicated by variations in laser sheet intensity, particle motion, and other optical factors. Because of the relatively low shutter speed and high velocity, droplets would appear as streaks in the image and be counted as a number of discrete identifications. Thus, the true number of droplets would be less than the number of identifications, however as all images were analyzed in the same manner under exactly the same conditions this should not have greatly affected ratios. No absolute measurement of droplet concentration was made, as we were primarily interested in the relative decrease in drops and total drop volume. No attempt was made to collapse the streaks into single droplet identifications. Different vocalizations such as "pop", "stop", "fish", "eee", "aah" etc., were tested with no mask, as well as rapid, heavy breathing with mouth held wide open, normally open, and with pursed lips. The vocalizations of "pop", "stop" and the breathing patterns were tested against a Sports Authority neck gaiter (used and washed approximately 15 times), an Under Armour sports mask, and both masks wetted with distilled water.

In the mask tests, the vocalizations were repeated in the following order: "pop", "stop", mouth wide open, mouth normally open, lips pursed, and lips pursed at a slower breathing rate. In the heavy breathing tests the volume was not measured, however it was likely somewhat less than the maximum exhalation volume of the subject measured to be 3.75 liters. The fast breathing rate was approximately 48 breaths/min and the slower rate was 33 breaths/min. In the wetting experiments, the face covering was first done "dry", and then was wet with distilled water using a spray bottle. Prior to "pop" the covering was wet with 8 squirts, corresponding to 5.1ml, and then after each vocalization one more squirt (0.64ml) was applied. This procedure appeared to saturate the surface of the face covering in the area over the mouth.

Results:

Vocalizations are well known to produce droplets of different sizes. Typically, plosive consonants such as "p" and "f" which are produced at the front of the mouth result in emission of larger droplets. Recent work by Stadnytskyi et al., (www.pnas.org/cgi/doi/10.1073/pnas.2006874117) suggests that the peak droplet emission for "st" in the vocalization "stay healthy" is approximately 25μm in diameter. In figure 2 we have plotted the number of particle identifications as a function of identified particle brightness for the vocalizations used in our study. We have also included the brightness of 50μm diameter glass spheres for comparison. For particles of this size, the brightness should roughly be proportional to the square of the diameter as well as a refractive index correction. Based on the brightness, the peak identifications for "stop" is about 23μm, for "pop" is about 15μm, and the small number of large droplets formed from heavy breathing with pursed lips is about 56μm. These size identifications are very uncertain, as the droplets are much too small to be resolved by our optical system. However these designations are consistent with earlier work.

Smaller droplets such as are produced by breathing alone or vowel sounds are too small to be resolved using our laser sheet system. This is further complicated by the observation that small droplets will dehydrate very rapidly to aerosols before reaching the laser sheet. Since approximately 99% of saliva is water, droplet nuclei have a diameter of roughly 1/5 of the original droplet. The hydrated droplet diameter of droplets emitted by breathing or by vowel sounds such as "aah" have been estimated by Asadi, et al. (https://doi.org/10.1038/s41598-019-38808-z) to be approximately 5μm. It is possible to see evidence of such droplets in our system, but only indirectly. It was apparent when conducting the experiment that there would be a very faint glow in the laser sheet during exhalation. By adding the unfiltered image brightness over the entire image, normalizing by the average value over 20 seconds, and subtracting one we obtain the result depicted in figure 3 for rapid breathing with mouth held wide

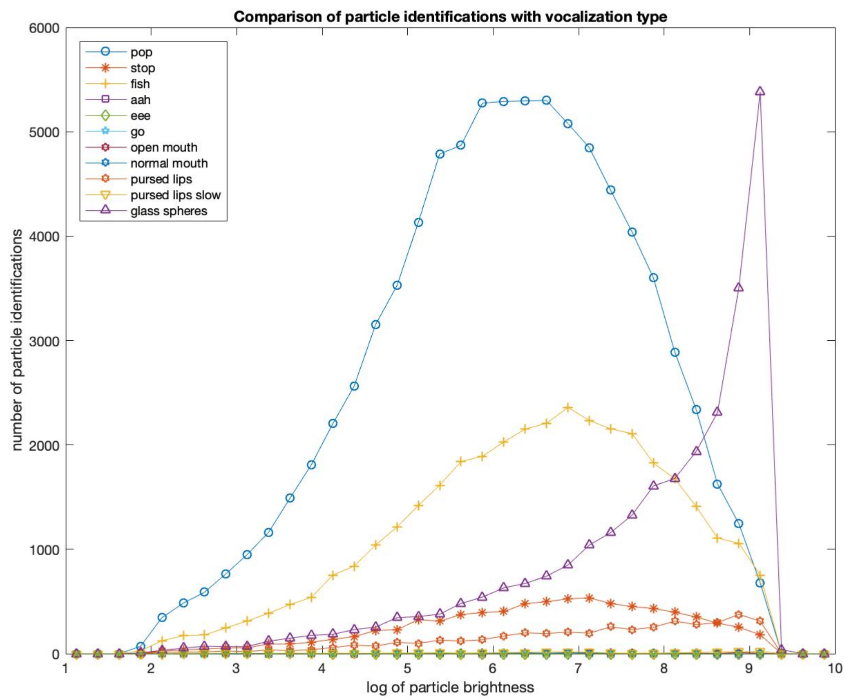

Figure 2. Particle Identifications for Different Vocalizations. x-axis is the log of the identified particle brightness in the image. Droplets appeared as streaks, so multiple identifications are made for each droplet.

open. Interestingly, the total image brightness reveals a slight elevation above black background associated with each breath (48 breaths/min) for both no mask and for the gaiter. Since there was no change, it suggests that the gaiter did not prevent the escape of droplets of O(5μm) in diameter. In contrast, both the Under Armour sports mask and Sports Authority gaiter wetted with water eliminated the variation, suggesting that particles of this size were successfully captured.

The performance of different masks against the vocalization "stop" is depicted in figure 4. It is apparent that the droplet emissions associated with this vocalization are effectively blocked in all cases. The performance of the masking strategies against the vocalization "pop" is depicted in figure 5. The result here is very different. The first "p" in the vocalization is plosive, beginning

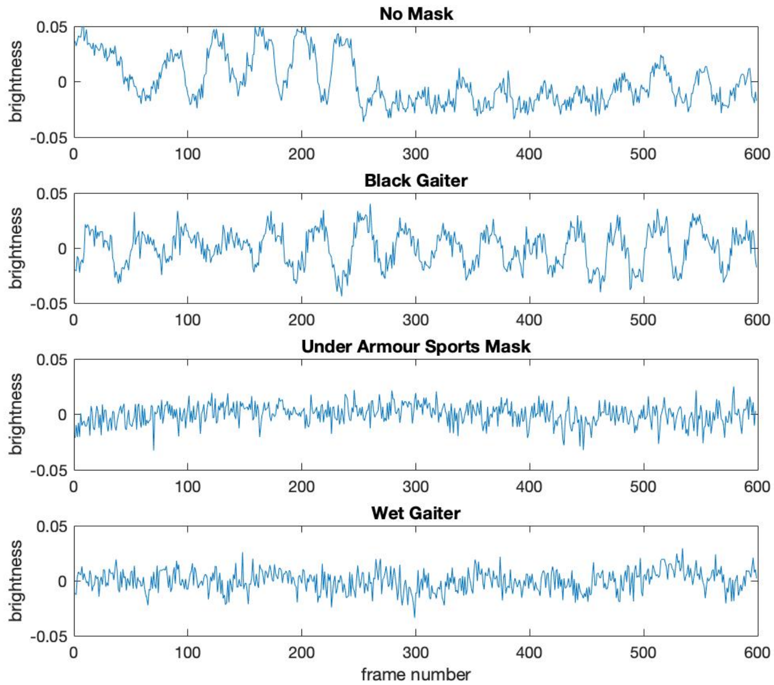

Figure 3. Total Image Brightness vs. Frame Number. The total image brightness reveals an approximately 5% increase over black background during each breath. The pattern is unaffected by the gaiter mask, however it is eliminated by both an Under Armour sports mask as well as a wet gaiter.

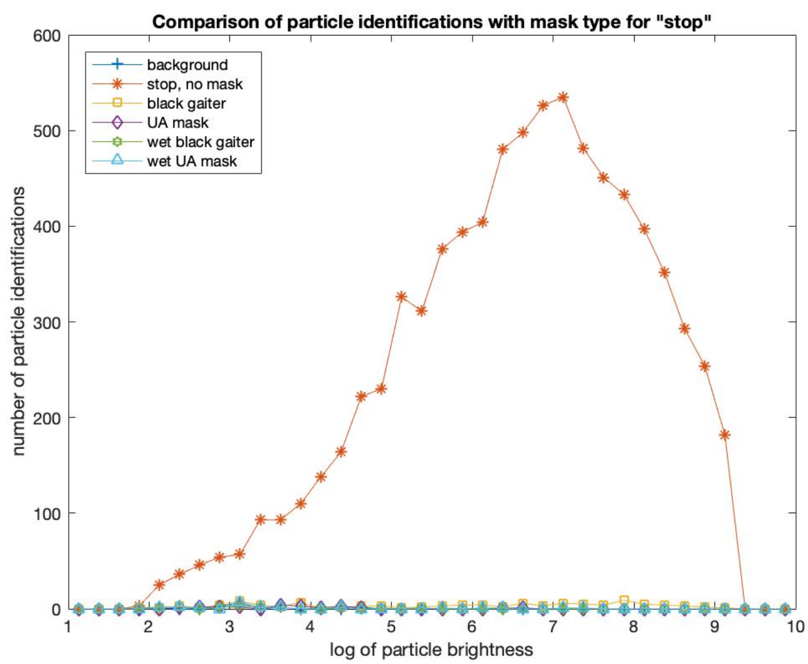

Figure 4. Particle Identifications for "stop". It is apparent that the droplet emission associated with the vocalization "stop" are effectively captured by gaiter and UA mask, both wet and dry.

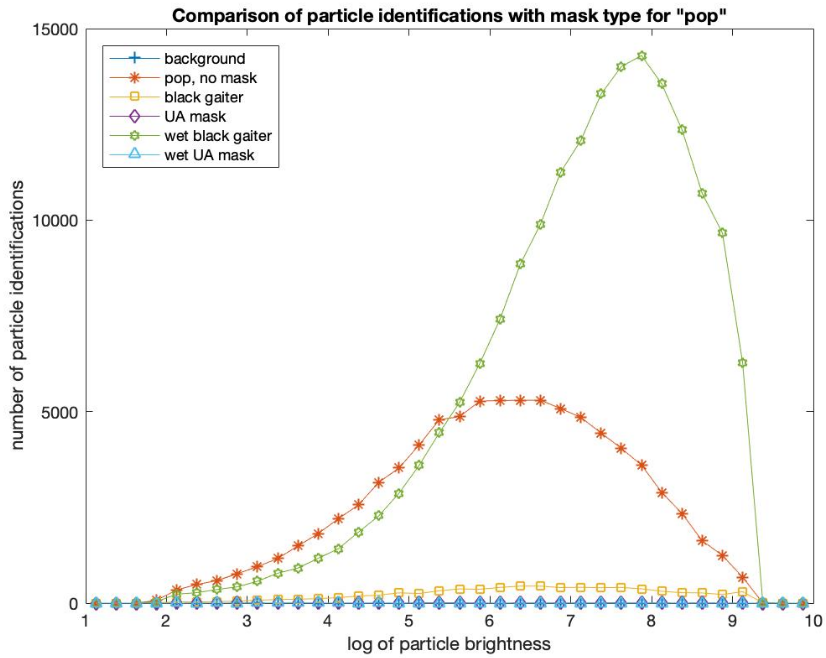

Figure 5. Particle Identifications for "pop". Some of the droplets produced in this vocalization escape a dry gaiter, however most are retained. For a wet gaiter a large explosion of droplets is observed.

with closed lips and emitting a small puff of air which carries the bulk of the droplet emissions. In the case of the Under Armour sports mask, wet and dry, the emitted droplets are apparently captured. For a dry gaiter a small fraction of the emitted droplets escape during this vocalization. The key result, however, is that for a wet gaiter there is an explosion of droplets with estimated diameter of 40μm emitted from the surface. The volume of droplets is much greater than the volume of liquid droplets emitted from the mouth during the vocalization, thus its source must be the water added to the surface of the gaiter.

The effect is even more startling when heavy breathing is examined. The time series of particle identifications for a wet gaiter and different vocalizations is depicted in figure 6. For the case of a mouth held wide open, a wet gaiter does not emit any observable droplets, as is the case for the vocalization "stop". For the vocalization "pop" and for rapid breathing with pursed lips a large number of droplets are observed. For rapid, heavy breathing with mouth held at a normal opening (difficult to do consistently) the droplet release sometimes occurred. Droplets were also released for heavy, somewhat slower (33 breaths/min) breathing. In both cases the droplet release was associated only with the beginning of the exhalation.

The volume of droplets by a wet gaiter for pursed lips was quite large, as is depicted in figure 7. There are a small number of droplets which are emitted in the case of no mask, and these are

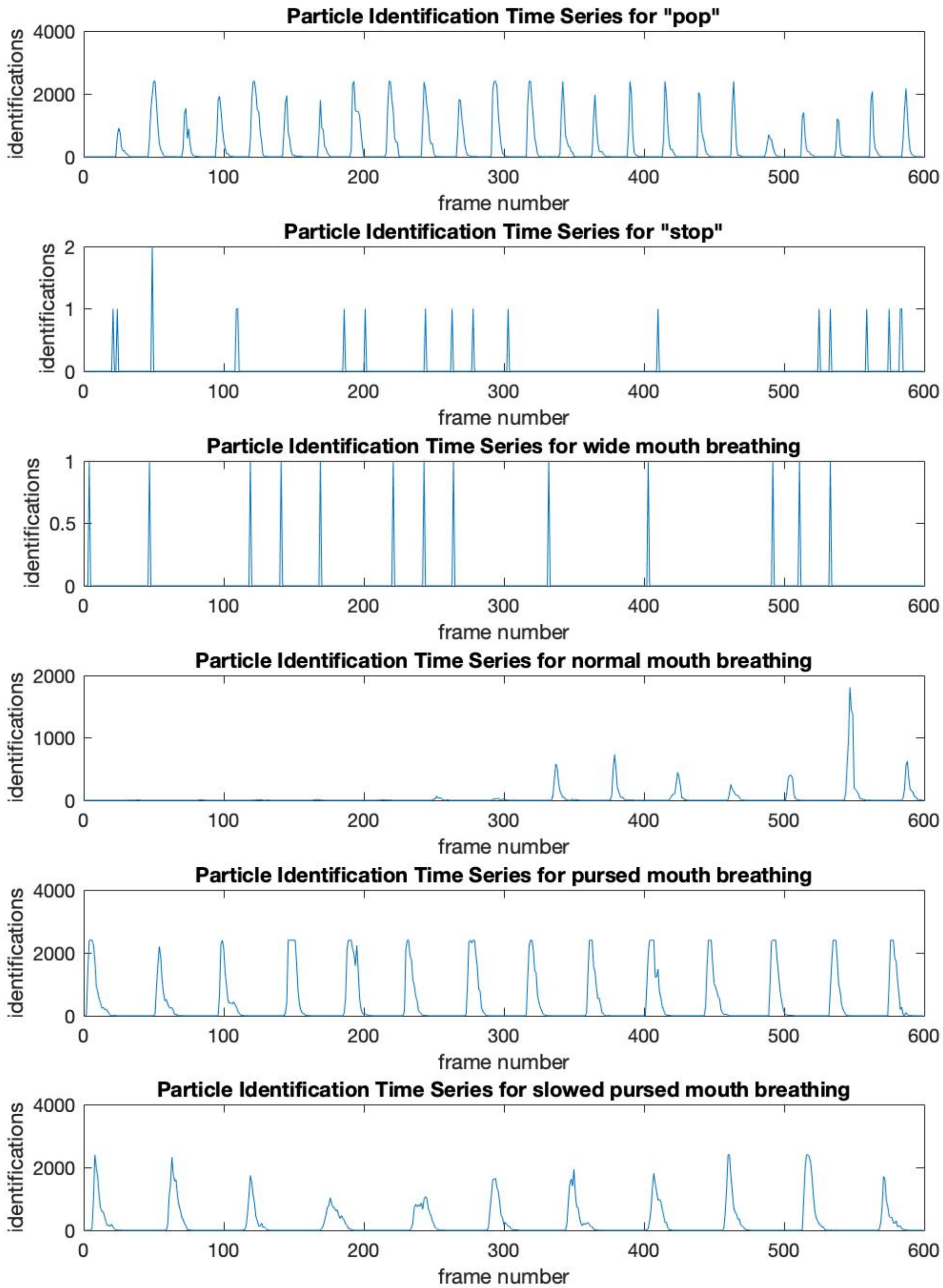

Figure 6. Time series for particle identifications with wetted gaiter. Few particles were identified for “stop” or open mouth breathing. Large emissions were identified for “pop”, normal opening, or pursed lips.

captured by the UA mask (wet or dry) and by the dry gaiter. A wet gaiter, on the other hand, emits a very large amount of liquid as an aerosol.

We may attempt to quantify the volume emitted in all of these experiments by using the measured droplet brightness as a rough measure of droplet size. If the brightness is proportional to the square of the diameter, and the volume proportional to the cube, then the volume of each drop is proportional to the brightness^1.5. This issue is complicated by faster moving drops appearing somewhat dimmer, however as they would have more associated particle identifications this effect should somewhat cancel out. In any event, this should give us a very rough figure of merit on the volume of emissions detected in each experiment. We normalize by the estimated drop volume associated with the vocalization "stop", enunciated loudly with no mask. This results in the observations depicted in table 1. Volumes less than 0.001 of the volume for "stop" are set to zero.

Table 1. Estimated droplet volume normalized by the vocalization "stop".

	No Mask	Gaiter	Wet Gaiter	UA Mask	Wet UA Mask
"stop"	1.0	0.01	0	0	0
"pop"	6.28	1.01	33.8	0.013	0
wide open	0.02	0.001	0	0.001	0
normal	0.005	0	2.52	0	0
pursed lips	1.07	0.32	29.9	0	0
pursed slow	0.06	0.006	10.0	0	0

Table 1. Droplet emission volume estimated from particle identifications and brightness are compared for different vocalizations and mask type. All volumes are normalized by the volume estimated for the vocalization "stop" with no mask.

Discussion:

It is apparent from the volume estimates in Table 1 that a dry gaiter is somewhat effective in blocking droplets emitted by speech, particularly if the velocity is not too high. The droplets associated with the verbalization "stop" were reduced by 99%. For more vigorous vocalizations such as "pop" and exhaling through pursed lips, some 70% of the droplet volume was captured. Based on the overall image brightness measurements, the dry gaiter had little effect on the very small droplets produced in breathing with a wide open mouth. The UA sports mask when dry eliminated more than 99% of the measurable droplet volume in all cases, only allowing a small amount through in the vocalization "pop". For a wet UA mask there was no significant amount of droplet emissions detected under any circumstances.

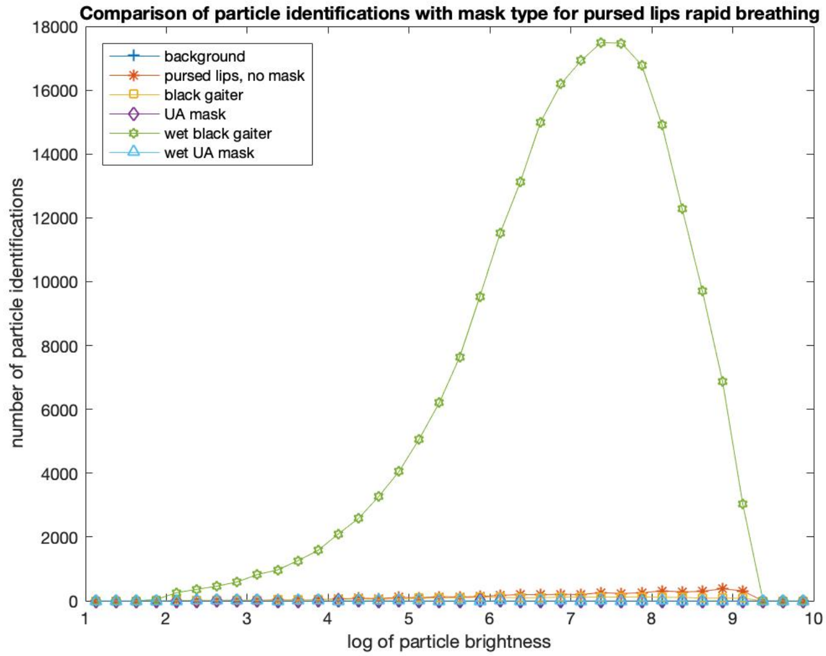

Figure 7. Droplet emission for rapid breathing with pursed lips. A small number of drops are emitted in the absence of a mask. A very large volume of drops are emitted from a wet gaiter in this vocalization.

The situation is much more complex for the wet gaiter. For very small drops produced by breathing with a wide open mouth it actually does better than a dry gaiter. This should not be surprising, as the wetting of the fibers would improve the capture of micron sized drops, much the way breathing through a wetted cloth is recommended when trying to escape from a smoke filled room. For more intense vocalizations and breathing, however, the situation is very different. It is likely that there is a critical pressure that must be applied by expelled air onto the inside surface of the gaiter to enable atomization of liquid and the thus large scale production of aerosols. The volume of these aerosols is quite significant, easily the equivalent of an unprotected cough at every breath. The key appears to be the opening of the mouth and the details of the air release. A plosive consonant such as the first "p" in "pop" begins with the mouth closed and, due to the elasticity of the gaiter, the gaiter is in contact with the lips. Thus, as the "p" is vocalized the air is forced through the gaiter material, leading to the aerosol production. In the case of "stop", just as loudly vocalized, the "st" sound begins with the lips parted. Thus, air can escape the region immediately in front of the lips and the pressure never reaches the critical value that causes rapid flow through the fabric. The same thing occurs with heavy breathing: with a mouth wide open there is no aerosol production, but as the distance between the lips decreases the amount of aerosol production explodes. For the UA mask, on the other hand, its design keeps it some distance away from the lips so this explosive release of drops does not occur. These results are general: although we have only presented the results for a washed Sports Authority gaiter, we have found the same behavior for a new (unwashed) gaiter, as well as an ND logobrand gaiter. We have also found ND logobrands reusable cloth masks, Sanda disposable masks, and home made two-layer cloth masks to behave comparably to the UA mask discussed here. Experiments with the two-layer cloth mask were revealing: we could achieve an explosive release of droplets with heavy breathing, but only if the mask were forced onto the lips during exhalation.

It is important to consider the implications of these experiments to a "real world" environment. If used in heavy exercise a gaiter will get wet with both sweat and saliva. As it gets wet, the resistance to air flow increases and the gaiter is actually sucked into the mouth during inhalation. This naturally leads to the wearer closing lips during inhalation, and thus pursed lips during exhalation. The close contact between the gaiter and the lips would also cause wicking of saliva directly from the mouth to the gaiter. Thus, while most of the gaiter is soaked in sweat (and thus virus free), the portion of liquid around the lips which is converted to an aerosol is likely primarily saliva and could carry a significant viral load.

The bottom line is fairly simple: if an infected athlete is wearing a wet gaiter during heavy exercise they would be emitting aerosols containing viral particles comparable to an unprotected cough with every exhalation. This is orders of magnitude greater than the relatively small emission from heavy breathing without wearing a face covering at all. Thus, gaiters are not recommended under these conditions.

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