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Letter

Performance of Valved Respirators to Reduce Emission of Respiratory Particles Generated by Speaking

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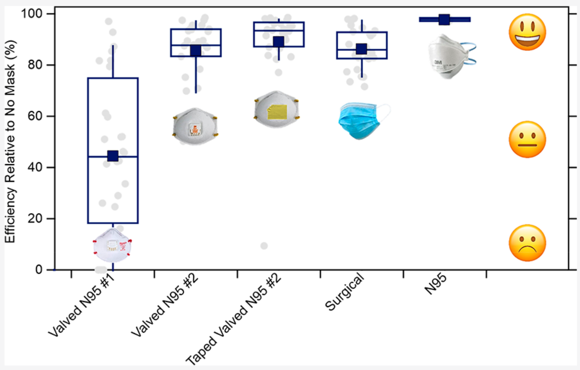
ABSTRACT: Wearing of face coverings serves two purposes: reducing the concentration of ambient particles inhaled and reducing the emission of respiratory particles generated by the wearer. The efficiency of different face coverings depends on the material, design, and fit. Face coverings such as N95 respirators, when worn properly, are highly efficient at filtering ambient particles during inhalation. Some N95 respirators, as well as other face covering types, include a one-way valve to allow easier exhalation while still maintaining a high efficiency of filtration of inhaled ambient particles. The extent to which these valves decrease the efficiency of filtration of emitted respiratory particles is, however, not well established. Here, we show that different valved N95s exhibit highly variable filtration efficiencies for exhaled respiratory particles. As such, valved N95s may not provide reliable source control of respired particles and their use should be discouraged in situations in which such source control is needed.



KEYWORDS: *face coverings, masks, respiratory particles*

INTRODUCTION

Face coverings reduce the concentrations of both inhaled and exhaled particles, and their efficiencies vary by design and type. In many settings, the primary purpose of face coverings, generically termed masks, is to protect the wearer from inhalation of ambient particles that might be toxic or otherwise unhealthy.[1] Generally, cloth masks and medical procedure masks do not provide the same level of protection as a well-fit respirator (e.g., N95 filtering facepiece respirators) for inhaled ambient particles.[2−5] Some N95 respirators, as well as other types of face coverings, include an exhalation valve, the purpose of which is to facilitate easier breathing and reduce the humidity and temperature inside the mask interior volume while still providing protection to the wearer against inhalation of ambient particles.[6,7] The inclusion of an exhalation valve makes sense if the primary purpose is to protect the wearer, so long as it does not affect the mask filtration efficiency toward inhaled ambient particles. However, as the ongoing COVID-19 pandemic has made clear, masks also provide another important function, namely source control via reduction of the emission of potentially infectious respiratory particles[8,9] that are produced during breathing, speaking, coughing, or sneezing.[10,11]

In this context, it is critical to understand the extent to which an exhalation valve reduces mask efficiency toward exhaled respiratory particles and to compare their performance with that of other mask types. Staymates provided qualitative evidence that valved N95 respirators lead to excessive escape of respiratory particles and therefore a substantial reduction in their efficiency.[12] National Institute for Occupational Safety and Health (NIOSH) researchers performed experiments using test aerosol to challenge various valved respirators firmly sealed around their edges to a surface. In contrast to Staymates,[12] the NIOSH researchers found relatively high efficiencies (~70%), despite the presence of the valve, although it is possible that the valves in the respirators used may have remained mostly closed during testing leading to artificially high efficiencies.[13] Additionally, these measurements considered performance under ideal conditions (perfect sealing) and did not address performance when worn by people. Asadi et al. provided measurements of the effectiveness of a vented N95 respirator toward exhaled respiratory particles when worn by people, finding reasonably good performance.[14] However, their measurements were limited to only two people and one respirator type. Also, they measured particle emissions only in the forward direction and may have undersampled any particles that escaped through the valve.

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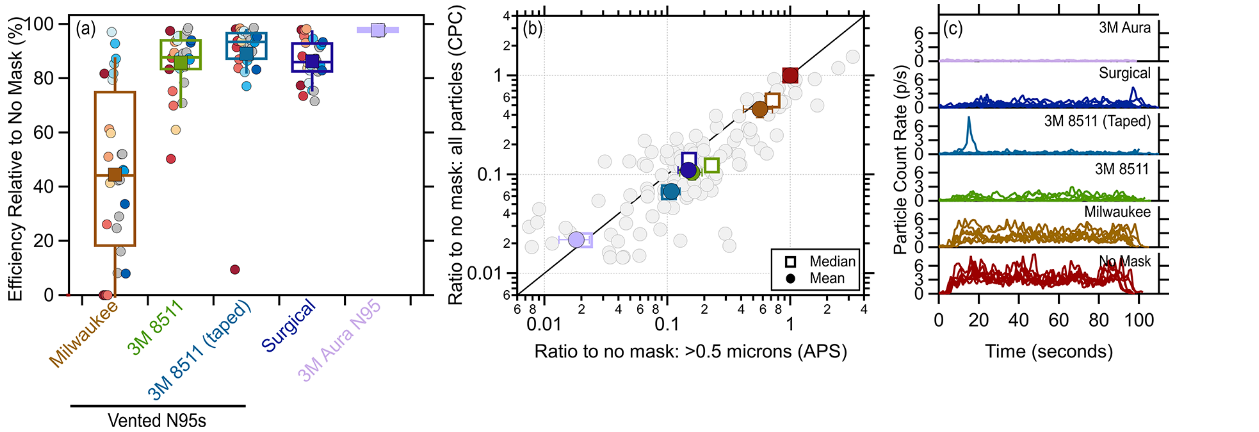

Figure 1. Observations of the reduction in the concentration of respiratory particles emitted during speaking with wearing of various mask types. (a) Mask efficiency results for all participants, with colored points corresponding to different individuals. Results for one individual repeating the task many times are colored gray. The box and whisker plots show the median (horizontal line), 25th/75th percentiles (boxes), and 10th/90th percentiles (whiskers), along with the geometric mean (square). (b) Relationship between the particle reduction ratio determined from the CPC and the APS, with all results colored gray, geometric mean values shown as colored circles, and medians shown as colored squares. (c) Observed time series of CPC-measured respiratory particle emission rates from speaking associated with the gray data from panel a. Note that these have not been corrected for dilution.

Providing the public with clear guidance regarding appropriate mask wearing to reduce both inhaled and exhaled particle concentrations requires a clear understanding of the reduction afforded by valved respirators when worn by actual people while speaking. Speaking is one of the most common respiratory particle generating processes that leads to emission of particles at about 10 times the rate of breathing.[10] Here, we address this issue by taking measurements of the reduction in respiratory particle concentrations generated by people when speaking afforded by wearing of different masks, including readily available (in the United States) valved N95 respirators.

MATERIALS AND METHODS

Employing from the methods used by Cappa et al. and other associated works,[10,14−16] we measured the concentrations of respiratory particles emitted while speaking by 10 individuals ranging in age from 20 to 43 with four self-identified females and six self-identified males. The University of California Davis Institutional Review Board approved this study (IRB# 844,369-4), and all research was performed in accordance with relevant guidelines and regulations of the Institutional Review Board. The participants spoke the *Rainbow Passage* while either not wearing or wearing one of four face coverings: a surgical procedure mask (ValuMax, model 5130E-SB), a valved 3M N95 respirator (model 8511), the same 3M 8511 N95 but with the valve taped over in the mask interior, or a valved Milwaukee N95 respirator (model 48-73-4011). These particular valved respirators were selected as they are readily available to the public in the United States. Participants were provided instructions for and guided toward proper wearing of the masks, but no formal fit test was conducted; the intent here is to consider masks as they might be worn by the public. To reduce the potential for sticking of the N95 respirator valves, the valve flaps were gently pushed out prior to the initial wearing.

A laminar flow hood (Air Science, PURAIR FLOW-48) housed the sampling funnel and provided HEPA-filtered air such that background particle concentrations were negligible. Figure S1 shows the experimental setup. Participants spoke with their face and the sides of the face coverings inside the outer circumference of a large (30 cm diameter) funnel from which an aerodynamic particle sizer (APS) [TSI, Inc., 5 L/minute (lpm)] and a condensation particle counter (CPC) (TSI, Inc., 0.3 lpm) continuously sampled along with an excess flow of 19.7 lpm, such that the total flow into the funnel was 25 lpm. The APS characterizes size distributions and concentrations of particles having diameters of >0.5 μm, while the CPC measures the concentration of all >0.01 μm particles. The stopping distance of 1 μm particles that escape from the mask edges is $\ll$1 cm, and thus, these will be predominately entrained into the airflow passing into the funnel, although particles may be carried further by the jets of airflow out the mask edges. The extent to which such particles were not sampled by the APS was characterized by measuring the CO_2 concentrations in the APS exhaust. The CO_2 concentration of exhaled breath is much greater than the ambient CO_2 concentration. The measured CO_2 concentration depends on how much of the 25 lpm total flow consists of exhaled breath and will be lower if exhaled air is not sampled into the funnel. These CO_2 measurements were made separately from the speaking experiments and for one participant only but using the same experimental setup. Further details regarding the methods are available in the Supporting Information.

Each participant performed two nonsequential replicates for each condition using the same mask, and the order of tests was varied between participants. One participant repeated these tests using different masks (e.g., multiple readings wearing different 3M 8511 respirators) to help establish whether between-participant differences derive primarily from differences in how the individuals wore the masks and spoke or from differences in the individual masks. This participant also performed the tasks wearing a nonvalved N95 respirator (3M, model Aura 9205+). The ratio (R_{mask}) between the particle concentration measured with wearing of a given mask and without provides a measure of the mask efficiency ($\eta_{mask} = 1 - R_{mask}$) for reducing emission of respiratory particles. When R_{mask} exceeded unity, η_{mask} was set to 0% as negative efficiencies are not allowed.

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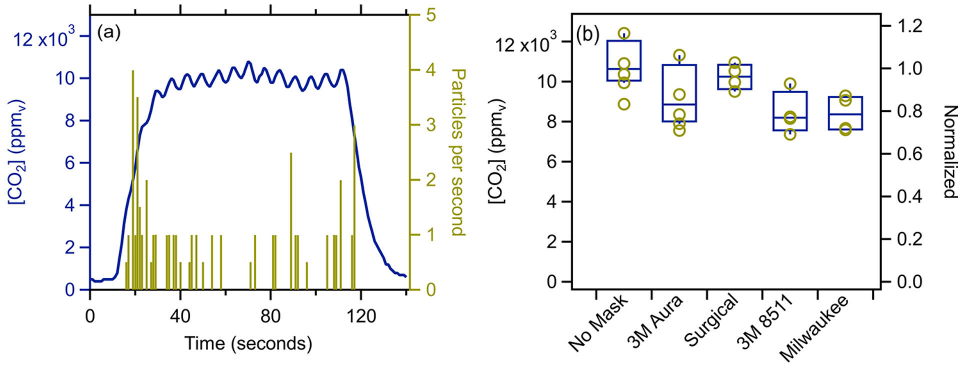

Figure 2. (a) Example time series of measured CO_2 concentration (blue) and particle counts (yellow) for ∼100 s of breathing with no mask wearing. The oscillations in the CO_2 concentration result from cycles of inhalation and exhalation. (b) Average CO_2 concentration measured for each trial for wearing of different face coverings. Individual results are shown as yellow circles, and the overall behavior is summarized with the box and whisker plot. Absolute CO_2 concentrations are shown on the left axis, and the corresponding values normalized to the median from no mask wearing on the right axis.

■ RESULTS AND DISCUSSION

With no face covering, measured particle concentrations and size distributions were consistent with previous observations,[10,11,15−17] with the CPC measuring on average 24 times as many particles as the APS, indicating that <0.5 μm particles dominate the overall number (Figures S2 and S3). Upon comparison of the observations across all participants, the median (or geometric mean) η_{mask} for all particles varied substantially between face covering types, with η_{mask} values of 45% (44%) for the Milwaukee, 86% (88%) for the 3M 8511, 89% (93%) for the taped 3M 8511, and 86% (85%) for the surgical masks (Figure 1a). The results for >0.5 μm particles were similar (Figure 1b). The multiple repeats by the one participant wearing different individual masks yielded similar results, included in Figure 1a, with example time series of particle count rates shown in Figure 1c.

The magnitude of the decrease in particle emissions during speaking while wearing a surgical mask is consistent with our previous findings,[15,16] albeit with a somewhat higher overall efficiency. The η_{mask} for the 3M 8511 was similar to that observed by Asadi et al.[14] for a different valved N95 respirator and in line with the range observed by the NIOSH researchers (73−82% at a flow rate of 25 lpm),[13] while that for the Milwaukee respirator was significantly lower. Taping over the valve in the mask interior for the 3M 8511 reduced the respiratory particle emissions by a factor of ∼2. The observed surgical mask efficiency was similar to that of the 3M 8511 mask and significantly better than that of the Milwaukee mask [based on paired t tests (Table S1)]. The trials by the participant who repeated the speaking tasks multiple times additionally indicate that wearing of the nonvalved 3M Aura N95 mask provided an excellent decrease in exhaled particle concentrations, with a median η_{mask} of 98% (Figure 1a).

The CO_2 measurements indicate that imperfect sampling of particles that escape from the mask edges may have led to some underestimate of the total particle emission rates with mask wearing, resulting in an overestimate of mask efficiency. Specifically, the CO_2 measurements (Figure 2) suggest potential low biases in the particle emission rates of 4% (surgical), 17% (3M Aura), 23% (3M 8511), and 21% (Milwaukee). The between-participant variability may exceed that observed here for one participant, and we cannot rule out the possibility that this contributed to some of the variability in η_{mask}. The somewhat low value of the nonvalved 3M Aura mask could indicate that some filtered air is also undersampled, implying the actual impact on measured particle emission rates is smaller than the CO_2 measurements suggest. The similarity of the three N95 respirators indicates the particle reduction efficiencies can be quantitatively compared in a relative sense, even if the absolute efficiencies are biased slightly low.

For a few participants, the particle concentrations with mask wearing exceeded that with no mask, which can occur when, e.g., skin−mask rubbing releases nonrespiratory particles (Figure 1b).[16,17] Alternatively, this could reflect natural variability in the emission of respiratory particles by individuals; for the participant who repeated the tasks multiple times, the ratio between the maximum and minimum observed particle emission rates equaled 1.6. The potential for nonrespiratory particle contributions means that the actual reduction afforded by the masks could be greater than the observations suggest. However, we have no reason to think that the Milwaukee mask led to significantly greater production of such nonrespiratory particles than the other masks as the fit and material were generally similar to those of the 3M 8511 mask.

The individual η_{mask} for a given mask type varied widely between participants for all mask types but most notably for the Milwaukee mask. In general, the variability in both the absolute concentrations (Figure S3) and the η_{mask} (Figure 1a) between participants greatly exceeded the difference in the replicates for an individual participant, consistent with previous observations for surgical mask wearing.[15,16] The greater variability between individuals could indicate greater consistency either in how the masks were worn or in the speaking activity performed by one participant than between participants.

The Milwaukee and 3M 8511 respirators both have their valve similarly positioned in the center. As such, the very different performance of these two valved respirators likely results from a difference in the ease with which the valve opens during speaking. This indicates that highly variable performance of different valved respirators, if worn by the public, is expected and with some models providing almost no reduction in the concentration of exhaled respiratory particles produced when speaking. The NIOSH results for test particles indicate that the η_{mask} values for valved respirators decrease as flow rate increases, suggesting that efficiencies for coughing would be even lower than those observed here for speaking.[13] Thus,

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although valved respirators can provide protection to the wearer against inhalation of ambient particles, the use of valved masks when source control of respiratory particles is also desired should be avoided in favor of masks with a higher efficiency toward exhaled particles, as is the case when the aim is the reduction of respiratory disease transmission.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.2c00210.

Additional experimental details (particle background, participant demographics, and experiments with CO_2), a statistical comparison between mask types, and figures showing average particle size distributions, absolute particle emission rates, and the impact of the particle background (PDF)

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Author Contributions

J.M.H. and C.D.C. conducted the experiments. C.D.C. conceived the research, analyzed the data, and wrote the paper with contributions from J.M.H.

Notes

The authors declare no competing financial interest.

An earlier version of this work was submitted to a preprint server.[18]

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