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Can disposable masks be worn more than once?

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\textbf{A R T I C L E  I N F O}

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\textbf{A B S T R A C T}

Disposable facemasks are a primary tool to prevent the transmission of SARS-CoV-2 during the COVID-19 pandemic. However, plastic waste generated from their disposal represents a significant environmental problem that can be reduced by maximizing the service life of disposable masks. We evaluated the effect of repeated wearing on the fitted filtration efficiency (FFE) of N95, KP94, KN95, and procedure/surgical masks. The FFEs of masks were compared following extended wearing with and without washing. Results reveal that most disposable facemasks can retain a high level of their baseline FFE after extended wearing, even after 40 h of wearing. Laundering disposable masks degraded FFE in some instances. We conclude that the durability of disposable facemask performance is considerably longer than their intended single use indication, suggesting that reusing disposable masks is a safe means of reducing plastic waste in the environment.

1. Introduction

In response to the COVID-19 pandemic, global sales of disposable facemasks have increased 200-fold, generating a marked increase in the release of plastic waste into the environment (UNCTAD, 2021). Health and ecotoxicological risks associated with their production and improper disposal of disposable face coverings, such as endocrine disrupting effects and neurotoxicity, are well recognized (Patricio Silva et al., 2021; Du et al., 2022). Yet facemask usage remains a primary intervention to reduce personal exposure to pathogens during the COVID-19 pandemic, as well as to air quality emergencies such as wildfire smoke. Although reusable cloth masks have an advantage in sustainability of materials and easiness to clean, they tend to be more porous and looser fitting, and have been shown to provide poor performance compared to disposable facemasks and respirators that offer better fit and are constructed of materials with higher filtration efficiency (Clapp et al., 2021; Prince et al., 2021; Sickbert-Bennett et al., 2021). Indeed, high performance disposable masks (e.g., N95 respirators, KN95 and KP94 masks) offer the best protection against SARS-CoV-2 infection (Andrejko et al., 2022). Their demonstrated effectiveness in protecting public health creates a compelling need for a strategy that reduces the environmental impact of their disposal (Patricio Silva et al., 2020). Given that a single reuse reduces the consumption and disposal rate by half, maximizing the effective service life of disposable facemasks is an applicable strategy to mitigate the current global plastic waste problem.

Although mask manufacturers and workplace guidance currently recommend against the reuse of disposable facemasks, supply shortages forced hospitals to consider sterilization (e.g., autoclaving, treatment with ethylene oxide or hydrogen peroxide) and reuse of N95 respirators early during the COVID-19 pandemic (Sickbert-Bennett et al., 2020). However, information on the durability of the effectiveness of disposable face coverings available to the public is scarce. Decontamination studies on N95 material filtration suggested that laundring is inadvisable (Viscusi et al., 2007; Grillet et al., 2021). In this experimental study, we assessed the durability of the fitted performance of disposable

\textit{Abbreviations:} CNC, Condensation Nuclei Counter; EPA, Environmental Protection Agency; FFE, fitted filtration efficiency; OSHA, Occupational Safety and Health Administration.

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faceremasks after repeated wearing and machine washing.

2. Methods

Fitted filtration efficiency (FFE) testing of aerosol particles was conducted as previously described (Sickbert-Bennett et al., 2020; Prince et al., 2021). Briefly, a custom-built stainless exposure chamber was used to conduct the U.S. Occupational Safety and Health Administration (OSHA) Quantitative Fit Testing Protocol. Facemask FFE was measured with the subject bending at the waist, reading aloud, and moving their head. The chamber atmosphere was supplemented with sodium chloride particles with a smaller (median diameter: approximately 50 nm) or larger (median diameter: 164–346 nm) size. Two condensation particle counters (Model 3775, TSI) measured behind-mask or ambient counts. The study was approved by U.S. EPA Human Subject Research Review as “non-human subject research” (HSR-001231).

Volunteer staff members (n = 6, 3 females, 3 clean-shaven males, 3 Asian, 3 Caucasian, age 32–57) wore four facemask types: ear-loop non-medical procedure mask (Jiangsu Jianyu Health Medical, Jiangsu, China), KN95 mask (Shenzhen BAK Medical Technology, Guangdong, China; or Shanghai Dasheng, Shanghai, China), KP94 mask (Dr. Puri, Gyeonggi-do, Korea), and an N95 respirator (3 M 9205+, St. Paul, MN or Honeywell DC300N95, Charlotte, NC). Ear-loop masks were tightened behind the head using a paperclip to reduce variability in fit related to differences in facial morphology (Clapp et al., 2021).

The study comprised three experiments: (1) Wear/Wash: Facemasks were first tested after 0 (baseline), 8, 16 and 24-hr of wear, and machine washing after each full day of wear (2 rounds total; room-temperature water, delicate cycle with unscented detergent followed by extra washing after each full day of wear (2 rounds total; room-temperature water, delicate cycle with unscented detergent followed by extra rinsing and air drying at room temperature over the weekend); (2) Wash only: FFE was assessed with the facemasks subjected to 0–2 washes; and (3) Wear only: Facemasks were tested after up to 40 h of wear. Each 8-hr wear period comprised a single weekday, with volunteers engaging in everyday activities that included office work, errands, and aerobic exercise. During wear, aluminum testing ports were covered with a plastic cap. Between test sessions, masks were stored in a paper or mesh laundry bag.

Statistical analyses consisted of repeated-measures one-way ANOVA with Dunnett’s multiple comparisons test performed using GraphPad Prism 9 (San Diego, CA) (p -value < 0.05 considered statistically significant).

3. Results

In Experiment 1 testing using small (~50 nm) particles, we found that 8 h of wear yielded largely similar FFE compared to baseline (Fig. 1). After repeated wearing (16–24 hr) plus 1–2 washing cycles, the FFE of procedure and KP94 masks showed statistically non-significant decreases from baseline. KN95 masks which averaged 92.3% FFE after 8-hr wear, declined significantly after 16-hr of wear and 1 wash (85.7%, p = 0.011), and 24-hr + 2 washes (83.7%, p = 0.029). The 3 M N95 respirator also declined significantly, in this case from baseline FFE of 99.4 to 94.7% (p < 0.005) after 24-hr wear and 2 washes.

Additional experiments were then conducted to examine the influence of washing alone or wearing alone, and to test against both smaller (~50 nm) as well as the more challenging larger (>150 nm) particles to better assess the electret function of the masks. As shown in the top portion of Table 1 (Experiment 2 – Repeated washing), the FFE tended to decrease commensurately with the number of washes, regardless of the particle size used for testing. Compared with baseline testing, after one and two washes, the FFE against smaller particles yielded decreases of 12.5% and 14.3% for procedure masks, 9.2% and 2.2% for KN95 masks, 11.6% and 17.5% for KP94 masks, and 0.0% and 4.5% for N95 respirators, respectively. Relative to the percentage declines observed with smaller particle testing, the decrements in FFE against larger particles tended to be lower overall. The procedure mask, which started with higher baseline performance when tested against larger particles, was the exception for this trend.

We next examined the effect of prolonged wearing alone on face coverings, from incremental longitudinal wear (0–40 h) as tested against larger particle sizes (Fig. 2). Procedure, KP94 and N95 (3 M) masks performed at relatively similar levels after 8, 16, 24, 32, and 40 h of wear. KN95 masks also showed stable FFE versus baseline levels across extended wear time. However, the Honeywell N95 showed a steady decrease in FFE as a function of time of wear relative to baseline levels. As shown in the bottom portion of Table 1 (Experiment 3 – Repeated wearing), relative to baseline performance, the magnitudes of the decrements in FFE measured following 40 h of wear were not as great as those associated with washing (Table 1). However, they were similarly more pronounced against smaller particle versus larger particle testing, consistent with a previous report (Reponen et al., 2011), with procedure and Honeywell N95 masks showing bigger FFE declines.

4. Discussion

Given the unpredictability of SARS-CoV-2 variants, and expected increase in frequency of extreme air pollution exposure, it is likely that facemasks will remain a critical public health tool against viral and other airborne threats (CDC, 2021). Independent evaluation of disposable face coverings performance beyond their intended single use is needed to mitigate environmental health and ecosystem risks related to plastic waste (Allison et al., n.d.).

The non-woven polypropylene composition of N95, KP94, and KN95 masks underlies their superior performance relative to cloth masks (Clapp et al., 2021), in part from electrostatic properties of the polypropylene fibers, which trap submicron particles. Extended wear and laundering of a disposable mask may degrade its electret function leading to decreased mask performance (Grillet et al., 2021; Charvet et al., 2022). To address this concern, we evaluated the FFE of four types of facemasks after repeated wear and/or washing. We found that the fitted performance of procedure, KP94, KN95, and N95 showed decreasing trends after repeated wear and washing, with some reaching statistical significance. While variable, these results suggest that mask performance declined and may not endure repeated wear/wash cycles well. Results from the machine washing-alone experiment corroborated the notion that washing may decrease material filtration due to loss of electret function (Grillet et al., 2021; Charvet et al., 2022).

The effect of extended wear alone on FFE was also evaluated in this study. We found that all masks retained relatively high levels of their baseline FFE performance after up to 40 h of wear, consistent with findings that N95 respirators can provide adequate protective efficacy.
These factors may underlie the larger variance seen in the KN95 data. Increasing wear time may be related to decreased rigidity of the material against aerosol infections after a 3-day wear. (Du et al., 2020). Factors influential safe extended wear likely include design, construction, and material quality. Apparent slight improvements for KN95 masks with increasing wear time may be related to decreased rigidity of the material and metal nosepiece which allows for better fit against facial contours. These factors may underlie the larger variance seen in the KN95 data.

While “breaking in” or material softening may aid the fit for rigid masks, it may negatively affect the performance of more flexible masks or those lacking substantial reinforcement around the nose. For example, we observed steady decreases of FFE in the Honeywell N95 respirator, likely due to the absence of a metal nosepiece and foam to seal gaps around the nose (see supplementary material). It has also been shown in a hospital setting that N95 performance may decline with increased number of shifts/wears (4 vs. 2), increased times donning and doffing (15 vs. 8), and increased hours of wear (14 vs. 12) (Degesys et al., 2020).

Taken together, although overall performance remains high relative to other types of face coverings such as reusable cloth masks, household laundering of disposable facemasks resulted in FFE performance losses. By contrast, extended wear of disposable mask without additional intervention can maintain relatively high levels of performance. Improving the fit and function of sealing surfaces could help ensure sustained filtration performance for a broader variety of mask styles that may otherwise show deficits with extended use. Extending the lifespan intervention can maintain relatively high levels of performance.

| Treatment | Smaller particles (<50 nm) | Larger particles (>150 nm) |
|-----------|-----------------------------|-----------------------------|
|           | Mean | % change from baseline | Mean | % change from baseline |
| Procedure | Baseline | 72 | -12.5 | 81.0 | -15.2 |
| 1-Wash | 69 | -14.3 | 61.3 | -24.2 |
| 2-Wash | 61.7 | -17.5 | 58.0 | -31.2 |
| KN95<sup>b</sup> | Baseline | 78.3 | - | 78.8 | - |
| 1-Wash | 71.1 | -9.2 | 78.1 | -0.9 |
| 2-Wash | 76.6 | -2.2 | 80.9 | 2.7 |
| KF94 | Baseline | 96.9 | - | 92.0 | - |
| 1-Wash | 85.7 | -11.6 | 84.8 | -7.9 |
| 2-Wash | 79.9 | -17.5 | 78.9 | -14.2 |
| N95 (3 M) | Baseline | 99.6 | - | 99.8 | - |
| 1-Wash | 96.6 | 0.0 | 99.7 | -0.1 |
| 2-Wash | 95.1 | -4.5 | 97.6 | -2.2 |

<sup>a</sup> One mask was tested per condition on one participant. Fitted filtration efficiency (FFE) using the Occupational Safety and Health Administration modified ambient aerosol CNC quantitative fit testing protocol (Modified Ambient Aerosol CNC Quantitative Fit Testing Protocol For Filtering Facepiece Table A—RESPIRATORS).

<sup>b</sup> These KN95 masks were sourced from Shenzhen BAK Medical Technology.

<sup>c</sup> These KN95 masks were sourced from Shanghai Dasheng.

Fig. 2. Wear only experiment: Fitted filtration efficiency (FFE) using the Occupational Safety and Health Administration modified ambient aerosol CNC quantitative fit testing protocol (Modified Ambient Aerosol CNC Quantitative Fit Testing Protocol For Filtering Facepiece Table A—RESPIRATORS). Results show mean FFE at Baseline (unused) and after up to 40-h wear using larger particle sizes (164–346 nm). Baseline measurement shows the mean ± SD from three separate tests of unused masks conducted at the beginning, approximate middle, and end of the wear only experiment. All data show results from one volunteer wearing a single mask, presented as mean ± SD (calculated using the 140 s sampling period). Error bars not visible for uppermost (3 M) N95 are 0.8, 0.9, 0.7, 0.9, 1.2, and 1.2 for baseline, 8-h, 16-h, 24-h, 32-h, and 40-h, respectively.

Table 1

| Mask type<sup>c</sup> | Treatment | Smaller particles (<50 nm) | Larger particles (>150 nm) |
|-----------------------|-----------|-----------------------------|-----------------------------|
|                       | Mean | % change from baseline | Mean | % change from baseline |
| Procedure | Baseline | 67 | -16.0 | 73.2 | - |
| 40-h | 56.3 | -10.6 | 70.4 | 4.4 |
| KN95<sup>b</sup> | Baseline | 86.9 | 11.6 | 94.8 | 3.7 |
| 40-h | 97 | -2.5 | 96.7 | -0.5 |
| KF94 | Baseline | 95.7 | - | 97.2 | - |
| 40-h | 93.3 | -0.5 | 99.7 | -3.2 |
| N95 (3 M) | Baseline | 99.5 | - | 99.9 | - |
| 40-h | 99 | -13.4 | 92.1 | -6.0 |
| N95 (Honeywell) | Baseline | 96.7 | - | 98.0 | - |
| 40-h | 83.7 | -13.4 | 92.1 | -6.0 |

<sup>a</sup> One mask was tested per condition on one participant. Fitted filtration efficiency (FFE) using the Occupational Safety and Health Administration modified ambient aerosol CNC quantitative fit testing protocol (Modified Ambient Aerosol CNC Quantitative Fit Testing Protocol For Filtering Facepiece Table A—RESPIRATORS).

<sup>b</sup> These KN95 masks were sourced from Shenzhen BAK Medical Technology.

<sup>c</sup> These KN95 masks were sourced from Shanghai Dasheng.

CRediT authorship contribution statement

Hao Chen: Conceptualization, Investigation, Data curation, Validation, Formal analysis, Visualization, Writing – original draft, Writing - review & editing. James M. Samet: Conceptualization, Investigation, Resources, Methodology, Writing – original draft, Writing – review & editing, Supervision, Project administration. Haiyan Tong: Conceptualization, Investigation, Methodology. Aiman Abzhanova: Investigation, Methodology. Ana G. Rappold: Formal analysis, Investigation, Supervision. Steven E. Prince: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing, Visualization, Project administration.
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Disclaimer

The research described in this article has been reviewed by the Center for Environmental Public Health and Environmental Assessment, EPA and approved for publication. The contents of this article should not be construed to represent agency policy, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2022.113908.

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