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Efficacy of powered air-purifying respirators (PAPRs) for source control of simulated respiratory aerosols

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Abstract

Background: Loose-fitting powered air-purifying respirators (PAPRs) are a popular alternative to the use of filtering facepiece respirators for health care workers. Although PAPRs protect the wearer from aerosol particles, their ability to block infectious aerosol particles exhaled by the wearer from being released into the environment (called source control) is unclear.

Methods: The source control performance of 4 PAPRs with loose-fitting facepieces were tested using a manikin that exhales aerosol particles. The PAPRs were tested by themselves and in combination with a face-worn product intended to provide source control (either a surgical mask or an N95 filtering facepiece respirator).

Results: Two PAPR facepieces with filtration panels significantly reduced the release of exhaled aerosols into the environment, while 3 facepieces without such panels did not. Wearing a surgical mask or respirator under the facepiece significantly improved the source control performance.

Conclusions: Most PAPR facepieces do not block aerosols exhaled by the wearer. Facepieces designed to filter exhaled particles can prevent aerosols from being released into the environment. Wearing a surgical mask or a filtering facepiece respirator under the facepiece can also provide source control, but PAPRs are not typically certified for use with masks and respirators.

Graphical abstract

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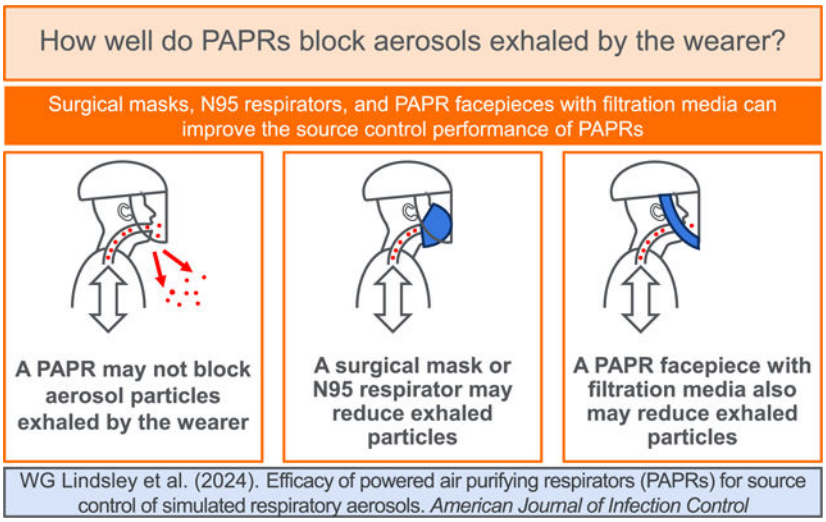
ATTRIBUTION STATEMENT

N95 and NIOSH Approved are certification marks of the U.S. Department of Health and Human Services (HHS) registered in the United States and several international jurisdictions.

APPENDIX A. SUPPLEMENTARY DATA

Supplementary data related to this article can be found at doi:10.1016/j.ajic.2024.07.019.



Keywords

Infection control; Airborne transmission; Surgical masks; Filtering facepiece respirators; Aerosol transmission; Occupational exposure

BACKGROUND

Respiratory viruses such as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and influenza are spread by aerosols expelled when infected people cough, sneeze, speak, or exhale.[1] Respiratory viruses have long been known to be spread by people who are symptomatic. However, during the coronavirus disease 2019 (COVID-19) pandemic, people who were infected but never developed symptoms (asymptomatic) or had not yet developed symptoms (presymptomatic) also were found to produce infectious aerosols, which hampered efforts to reduce transmission of the SARS-CoV-2 virus by isolation of symptomatic people.[2] Other respiratory viruses such as influenza virus are also suspected to be spread by asymptomatic and presymptomatic people.[3,4] Policies encouraging or requiring that everyone in public spaces wear a face mask or other face covering (called universal masking) were adopted during the COVID-19 pandemic in part as a way to reduce the transmission of SARS-CoV-2 virus by reducing the expulsion of infectious respiratory aerosols from asymptomatic and presymptomatic people into the environment (called source control).[5]

The exhalation of infectious aerosols by people without symptoms is particularly problematic in health care settings, both because health care workers can be exposed to airborne pathogens from patients and visitors who are asymptomatic, and because asymptomatic health care workers can inadvertently expose their patients to infectious aerosols. During the COVID-19 pandemic, filtering facepiece respirators such as N95 respirators were used to protect the wearer from infectious aerosol particles in the environment. However, if the person wearing the respirator has a respiratory infection, filtering facepiece respirators can also provide source control by blocking the release of

infectious aerosols by the wearer. This works because a well-fitting filtering facepiece respirator filters aerosol particles from exhaled air as well as inhaled air (so long as the respirator does not have an exhalation valve).[6,7]

Loose-fitting powered air-purifying respirators (PAPRs) are a popular alternative to the use of filtering facepiece respirators by health care workers because they are more comfortable and do not require a fit test.[8] Loose-fitting PAPRs can be broadly broken into 2 categories: facepieces that cover the top of the head and that have a clear face shield and a cuff around the face and jaw; and hoods that cover the entire head and neck and with a bib or shroud that covers some of the shoulders. While filtering facepiece respirators have an assigned protection factor of 10, indicating that in practice they are expected to reduce exposure to environmental aerosols by at least 90%, PAPRs with loose-fitting facepieces have an assigned protection factor of 25. PAPRs with loose-fitting facepieces, hoods, or helmets can be used by workers with facial hair or who cannot achieve a proper fit with a filtering facepiece respirator. However, unlike filtering facepiece respirators, most PAPRs do not filter the exhaled air from the wearer, and thus could potentially allow the release of infectious aerosols from the wearer into the environment.

A few studies have examined the possible contamination of sterile fields by health care workers wearing PAPRs. Howard et al[9] placed open agar plates around a simulated sterile field to collect aerosol particles that settled onto surfaces. Health care workers wearing surgical masks, PAPRs, or neither then performed various tasks. The authors found that sterile field contamination by workers wearing PAPRs was comparable to that seen when workers were wearing surgical masks. Brady et al[10] conducted a similar study and reported similar results. Myers et al[11] used an Andersen impactor (which uses a vacuum pump to pull in aerosols where they impact onto agar plates) to collect aerosols from people wearing masks, respirators, and PAPRs. They also found that bacterial contamination from people wearing PAPRs was not significantly different from people wearing surgical masks or N95 respirators without exhalation valves.

All 3 of these studies provide useful information about the source control performance of PAPRs. However, by design, the first 2 studies focused on aerosol particles that were large enough to quickly settle onto surfaces in the sterile field and contaminate them. The third study also focused on aerosols large enough to carry bacteria, and thus the mean diameters of the aerosols that they detected ranged from 4 to 10 μm. All 3 studies also measured only aerosols containing bacteria, which are primarily carried in larger respiratory aerosol particles than respiratory viruses.[12]

Smaller aerosol particles (< 4–5 μm), however, present a different problem: they do not settle quickly onto surfaces, but rather are able to linger in the air much longer. For example, a spherical aerosol particle that is 50 μm in diameter only takes about 13 seconds to fall 1 m, while a 5 μm aerosol particle takes 21 minutes and a 1 μm aerosol particle takes a full 8 hours to fall the same distance. Smaller aerosol particles also are easier to inhale and can deposit deeper in the respiratory tract,[13] and they are more difficult to block with source control products.[14]

Small respiratory aerosol particles are of particular concern in the transmission of respiratory viruses because several studies have suggested that, for at least some viruses, more virus is carried by smaller aerosols than by larger ones. A study by Yan et al[15] of exhaled breath from patients with influenza found 3 times more influenza viral RNA in aerosol particles smaller than 5 μm than in particles larger than 5 μm, while a second exhaled breath study found that particles smaller than 5 μm on average carried 12 times as much influenza virus.[16] An aerosol sampling study conducted in a hospital emergency department during influenza season found that 53% of the influenza viral RNA detected was in particles smaller than 4 μm.[17] Similar trends have been seen with the SARS-CoV-2 virus. Coleman et al[18] found that 85% of the SARS-Cov-2 virus detected in the exhaled breath of patients who were breathing, talking, or singing was in aerosol particles smaller than 5 μm, and Santarpia et al[19] found twice as much SARS-CoV-2 viral RNA in particles smaller than 4 μm compared with larger particles in aerosol samples collected from patient rooms.

The purpose of this paper is to examine how well PAPRs block small aerosol particles that are exhaled by the wearer from being released into the environment, and how this source control performance is affected by the addition of surgical masks or respirators or by the use of PAPR facepieces that are designed to function as source control products. This information will help health care workers and facilities determine how to best use PAPRs in patient care to protect both the workers and their patients during seasonal outbreaks and pandemics of respiratory viral diseases.

METHODS

Respiratory aerosol simulator

The experiments were done using an i-Bodi head-and-torso manikin (Crawley Creatures, Ltd) in an acrylic collection chamber (Fig 1). The manikin has an ISO medium standard headform shape[20] and soft elastomeric skin that mimics human skin. The aerosol and breathing airflow was produced using a method similar to that used by Li et al[21] and is described in detail in Figure S1 of the Supplementary Materials. The respiratory simulator had a breathing rate of 12 breaths/min and a ventilation rate of 15 L/min, which is the International Organization for Standardization (ISO) ventilation rate for a woman performing light work.[22] The concentration and size distribution of the test aerosol are shown in Table S1 in the Supplementary Materials.

Powered air-purifying respirators

The PAPRs tested were a convenience sample of commonly used commercially available products (Table 1). The PAPRs were tested with loose-fitting facepieces that cover the top of the head and the face and that have a cuff in front of the ears and under the chin. Four PAPRs were evaluated, including 1 PAPR that was tested with 2 different loose-fitting facepieces. Photographs of the PAPR facepieces are shown in Figures S2 to S6 in the Supplementary Materials. The facepiece for the Sentinel PAPR has vent holes under the chin to allow air to exit the facepiece, while the Versaflo PAPR facepiece has a permeable fabric mesh panel below the chin and the Maxair helmet and face cuff vents air near the ears. The Salus PAPR was tested with 2 facepieces; the first (referred to here as the

standard facepiece) has vent holes under the chin, while the second (referred to here as the high-efficiency particulate air (HEPA) facepiece) has a broad HEPA filtration panel under the jaw that is intended to filter the air flowing from the PAPR and thus provide source control.

Each PAPR was tested while the manikin wore no mask or respirator, a tie-on surgical mask (Medicom AssureMask Precision), or an N95 filtering facepiece respirator (3M model 9210, TC-84A-2669). Fit tests were not performed on the surgical masks or N95 respirators because it was not possible to perform the tests after the PAPR facepiece was donned without disturbing the facepiece.

NIOSH does not promote the use of 2 respirators for the purpose of respiratory protection. In this case, the N95 filtering facepiece respirator was tested as a source control product with the PAPR representing the product offering the respiratory protection. This condition was evaluated because N95 respirators are more effective than surgical masks at source control of small aerosol particles.[14,23]

Experimental procedure

For each experiment, a surgical mask or respirator (if needed) was placed on the manikin followed by the PAPR facepiece to be tested. The chamber door was then sealed, the optical particle sizer began collecting aerosol concentration data, and the chamber was purged with HEPA-filtered air for 10 minutes. The final 15 seconds of optical particle sizer data collected during the purge were used as the aerosol background concentration. After purging, the PAPR was turned on and the respiratory simulator began aerosol generation and breathing. The experiment continued for 20 minutes, which allowed the aerosol concentration at the outlet to reach a steady-state level. Each combination of PAPR, facepiece, and surgical mask or N95 respirator was tested 6 times, for a total of 162 experiments.

A single sample of each model of the PAPR blower was used for the experiments. PAPR facepieces were reused 3 times (once with no mask or respirator, once with a surgical mask, and once with an N95 respirator), except for the Sentinel facepieces, which were reused 6 times. The N95 respirators were reused 4 times, while the surgical masks were discarded after a single use to avoid untying and retying the masks. The PAPR facepieces, masks, and respirators were doffed and donned between each experiment.

Data analysis

For each experiment, the outcome measure was the steady-state aerosol concentration in the collection chamber. If the PAPR blocked a portion of the exhaled aerosol from entering the chamber (ie, provided source control), then the concentration would be correspondingly reduced. Because the concentration required 8 to 10 minutes to reach equilibrium, the first 10 minutes of data were discarded and the second 10 minutes of data were averaged. The aerosol background concentration was subtracted from the experimental data and the mass of the aerosol in each size bin per cm^3 of air (mass concentration) was calculated by multiplying the particle count by the volume of an individual particle based on the mean diameter of the size bin (assuming the particles were spherical) and the density of potassium chloride (KCl). Note that this conversion from particle counts to particle mass is commonly

used but is an approximation. The total aerosol mass/cm^3 (total aerosol mass concentration) was found by summing the aerosol mass concentrations for all the size bins. The mass concentration and particle number concentration data for these experiments can be found in the Supplementary Materials.

The source control performance, or source control collection efficiency, of a product like a PAPR or a face mask, is defined as the fraction of the mass of the respiratory aerosol that is blocked from entering the environment around the wearer.[6] The source control performance can also be described using the total outward leakage, which is the fraction of the respiratory aerosol that escapes past the product and into the environment.[24] For example, if 80% of the mass of the exhaled aerosol is blocked by a face mask and 20% of the aerosol mass flows through or around the mask into the air around the wearer, then the mask is said to have a source control collection efficiency of 80% and a total outward leakage of 20%.

The performance of each source control product was evaluated by calculating the collection efficiency as:

$$\text{Collection efficiency} = 1 - \frac{M_{product}}{M_{control}} \quad (1)$$

Where:

$M_{product}$ = average total mass concentration when testing the source control product.

$M_{control}$ = average total mass concentration while not wearing a source control product.

For each PAPR, the control aerosol concentration to which the other results were compared ($M_{control}$) was the equilibrium aerosol concentration measured with the blower running but with no facepiece and no mask or respirator. Because the PAPRs have different flow rates, $M_{control}$ was measured separately for each PAPR.

A 2-factor factorial design was used to examine the effects of the PAPR facepiece, mask, respirator, and their interaction for each PAPR blower. Post-hoc comparisons of the means for each pair of head cover with mask or respirator were made using Tukey's method. These data were generated using SAS 9.4 (SAS Institute, Inc).

RESULTS

The source control collection efficiencies for the different PAPRs, masks, and respirators are shown in Figure 2. A surgical mask worn without a PAPR facepiece had a collection efficiency of 28% to 41% in these experiments, while an N95 respirator worn by itself had a collection efficiency of 86% to 89%, indicating that wearing either the mask or the respirator significantly reduced the amount of respiratory aerosol that escaped into the collection chamber ($P < .001$ in all cases). The Sentinel PAPR had a collection efficiency of 11%, which was not significant ($P = .081$), but the collection efficiency increased to 37% when a surgical mask was worn with the facepiece and 87% when an N95 respirator was worn

with the facepiece, which was significant ($P < .001$ for both). The Maxair PAPR had similar results, with a collection efficiency of 9% with the helmet and face cuff alone ($P = .127$), 32% when a surgical mask was added under the face cuff ($P < .001$), and 79% when an N95 respirator was worn under the face cuff ($P < .001$). The Versaflo PAPR was more effective, with a collection efficiency of 55% for a facepiece worn without a surgical mask or N95 respirator ($P < .001$). The standard Salus facepiece had a collection efficiency of only 4% by itself ($P = .948$), but this increased to 47% when worn with a surgical mask ($P < .001$) and 86% when worn with an N95 respirator ($P < .001$). The Salus HEPA facepiece had a collection efficiency of 85% when tested by itself without a mask or respirator, 85% when worn with a surgical mask, and 96% when worn with an N95 respirator ($P < .001$ for all 3 combinations). Details about the comparisons of the different combinations are shown in Tables S3 to S6 in the Supplementary Materials.

DISCUSSION

PAPRs are respiratory protective devices that can protect the wearer from inhaling hazardous airborne particles. PAPRs are not typically designed to block the wearer's exhaled aerosol particles from being released into the environment and inhaled by others. However, the COVID-19 pandemic demonstrated the importance of source control to reduce the transmission of respiratory infections, especially in health care facilities. Thus, there is a need to better understand how well PAPRs perform as source control products and how their performance could be enhanced.

The Sentinel PAPR, Salus PAPR with the standard facepiece, and Maxair helmet and cuff did not provide effective source control when worn by themselves. The Versaflo facepiece did better, with a higher collection efficiency than was seen with the surgical mask. This most likely occurred because the Versaflo facepiece has a permeable fabric mesh panel below the chin that acts as a filter for air flowing out of the PAPR, rather than ventilation holes as in the Sentinel and standard Salus facepieces. The Salus facepiece with the HEPA panel, which was designed to filter exhaled aerosols, had a source control collection efficiency of 85%, which was substantially better than the other PAPR facepieces and the surgical mask, and comparable to that seen when using the N95 respirator by itself (86%−89%).

The addition of a surgical mask under the PAPR facepiece generally improved the source control performance compared with using a surgical mask by itself. Adding an N95 respirator under the facepiece led to a much greater improvement in source control performance compared with a surgical mask. These results suggest that combining a PAPR with a surgical mask or N95 respirator is potentially a way to accomplish both respiratory protection for the wearer and source control. However, adding a mask or respirator under a PAPR facepiece for source control presents at least one potential problem. All the facepieces have an elastic strip or plastic sheet that meets the face under and behind the jaw. If a mask or respirator is worn beneath the facepiece, the straps create a small break in this interface. This is especially true for the surgical mask, which has thicker tie-on straps as compared with the thin elastomer straps on the N95 respirator. One of the advantages of loose-fitting PAPRs is that they do not require a tight seal and can tolerate small gaps

while still providing respiratory protection (which is why they do not require fit testing). However, PAPRs are not designed for use with surgical masks or a second respirator, and one manufacturer does not recommend this approach for facepieces with a face cuff.[25]

Alternatively, source control features can be incorporated into the PAPR facepiece, as with the Salus facepiece with the HEPA filtration panel, to avoid the need to rely on additional face-worn products (ie, surgical masks or N95 respirators) to provide the necessary level of source control. However, the interface between the facepiece and the user's face then presents a different issue. Because loose-fitting PAPRs do not rely on a tight-fitting seal between the facepiece and the user's face, respiratory aerosols can flow out around the facepiece rather than through the filtration panels, reducing the source control performance. By necessity, any filtration material has some flow resistance, which increases the tendency for aerosols to flow out around the facepiece rather than through the filter. Thus, minimizing the gaps between the face and the facepiece is then necessary for effective source control. Tight-fitting PAPRs, which have facepieces that are designed to maintain a face seal, can be equipped with exhalation filters and thus also could be an effective way of providing both respiratory protection and source control.[26]

Finally, our study has several limitations. Our preliminary experiments showed that the collection efficiency of the surgical mask varied depending on how tightly the mask was tied to the face. All the masks in our experiments were placed by the same person and tied as consistently as possible, but this is a source of variability. For the test aerosol, 95% of the particles by mass were between 0.3 and 4.2 μm in diameter. This is the size range of potentially infectious aerosol particles most likely to remain airborne and most difficult to block with source control products. However, humans expel aerosol particles in a much broader range of sizes, particularly when coughing. It is likely that the source control collection efficiencies of the PAPRs would be higher for larger aerosol particles. Only one breathing ventilation rate was used for our studies, while ventilation rates vary from person to person and under different exertion levels. Only one head shape was used in our studies; heads with different facial dimensions and proportions could lead to different results. We did not examine the effects of head or face movements in our study. Some internal losses of test aerosol particles likely occurred within the collection chamber, which may have affected the estimates of the collection efficiencies. We only tested 5 PAPR facepieces, 1 surgical mask, and 1 N95 respirator, but many such products are available with a wide range of shapes and compositions, which would be expected to affect their individual performance.

CONCLUSIONS

Respiratory protective devices like PAPRs are designed to protect the wearer from ambient aerosol particles. However, the COVID-19 pandemic showed that, for contagious respiratory infections, source control of respiratory aerosols from the wearer can also be critically important. Wearing a surgical mask or filtering facepiece respirator underneath a PAPR can improve source control performance, but more work is needed to demonstrate that this does not compromise the respiratory protection provided. This study also provides early evidence that PAPR facepieces designed to provide source control may be an effective alternative that

does not require the use of additional products such as surgical masks or another respirator that is tight-fitting to achieve the necessary source control collection efficiency.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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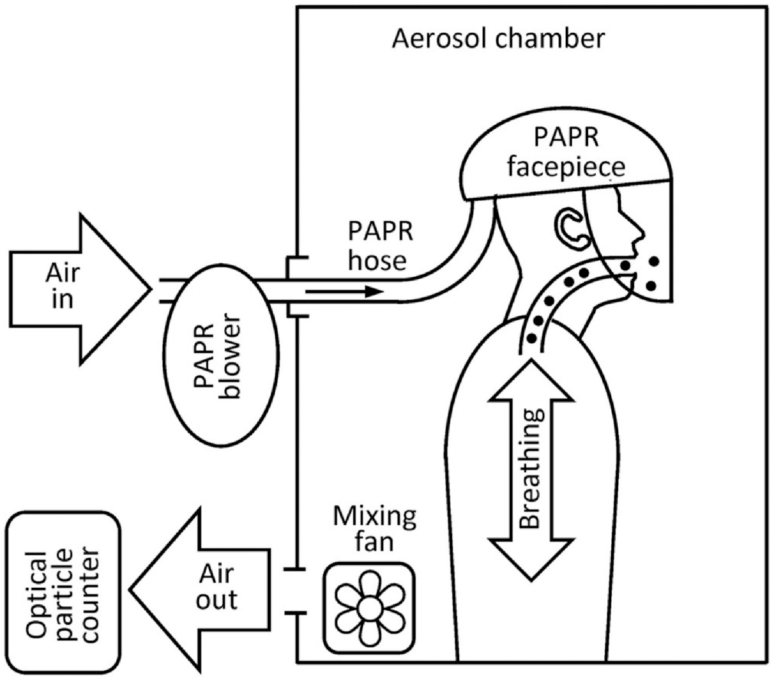

Fig. 1.

Experimental set-up for source control experiments. The collection chamber for the exhaled aerosol was an acrylic enclosure that measured 68 cm × 68 cm × 94 cm high (27″ × 27″ × 37″) on the inside. The chamber included a mixing fan behind the manikin to keep the air well-mixed during the experiments. The air from the chamber flowed out through a 6.4 cm (2.5″) port near the bottom of the enclosure, where the aerosol concentration was measured using an optical particle sizer (OPS; Model 3330, TSI). A blower with a HEPA filter was used to purge the chamber between experiments. The interior of the enclosure was wiped down with an antistatic solution (Staticide #2010, ACL Staticide). HEPA, high-efficiency particulate air; PAPR, powered air-purifying respirator.

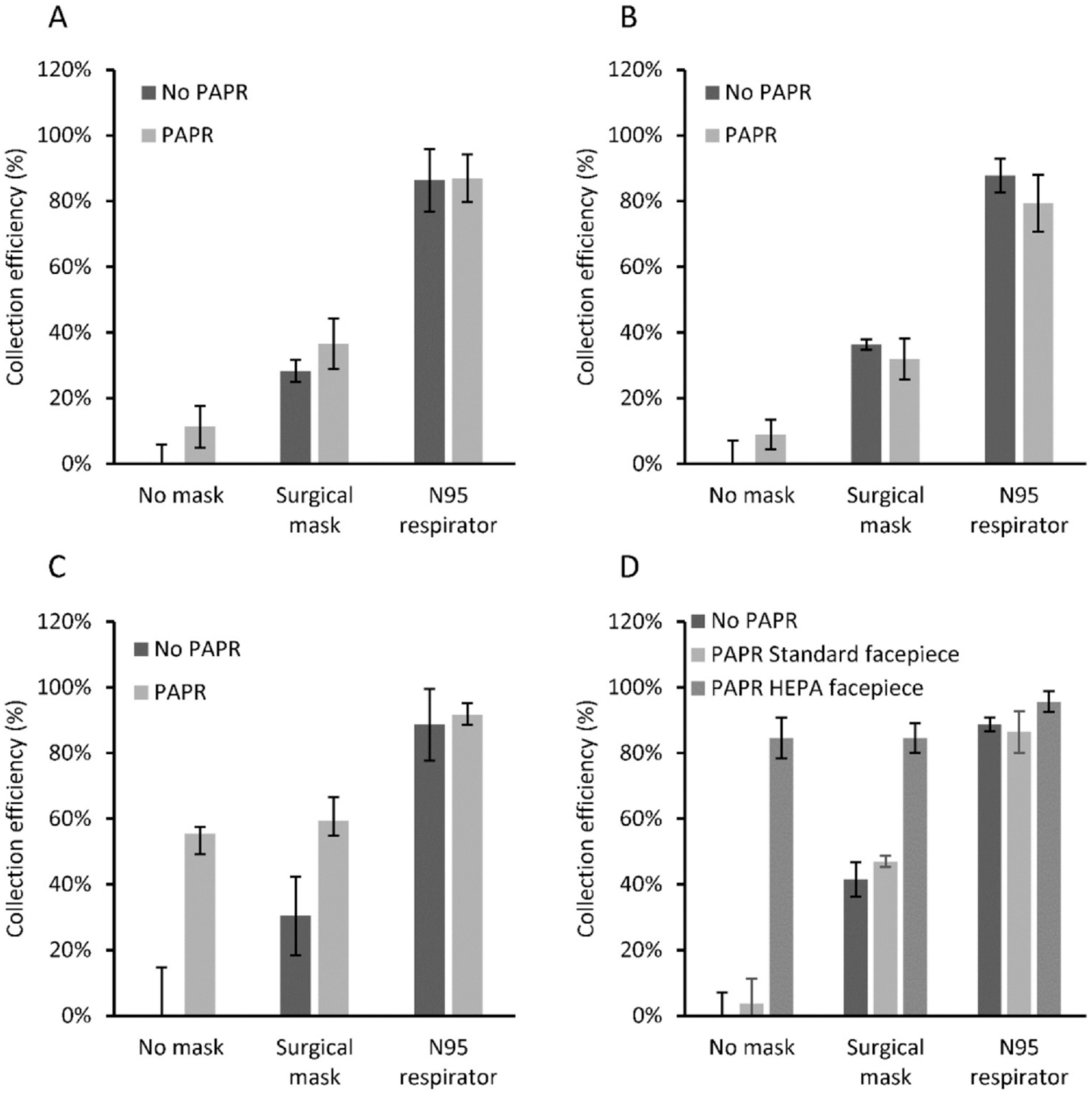

Fig. 2.

Source control collection efficiency of (A) ILC Dover Sentinel PAPR, (B) Syntech Maxair PAPR, (C) 3M Versaflo PAPR, and (D) Bullard Salus PAPR. Experiments were performed with the respiratory aerosol simulator wearing no mask, a surgical mask, or an N95 respirator and with or without a PAPR facepiece. For each PAPR, the experiments with no PAPR facepiece and no mask provided the baseline to which the other results were compared. PAPR, powered air-purifying respirator.

Table 1

PAPRs and facepieces used in the study

Manufacturer	PAPR	Airflow (L/min)	Facepiece	Mask or respirator used
3M	Versaflo	185	Medium/large facepiece with fabric mesh below chin	None Surgical mask N95 respirator
Bullard	Salus HC-M	215	Medium/large standard facepiece with vent holes below chin	None Surgical mask N95 respirator
			Small/medium facepiece with HEPA filtration panel below chin *	None Surgical mask N95 respirator
ILC Dover	Sentinel XP HP	230	Single-sized facepiece with vent holes below chin	None Surgical mask N95 respirator
Syntech International	Maxair	215	Helmet with medium/large lens cuff	None Surgical mask N95 respirator

NOTE. All the facepieces consisted of a transparent face shield, a covering over the top of the head, and a cuff that fits around the face. All PAPR ensembles were NIOSH-approved except for the Maxair, which has been submitted for NIOSH approval. Photographs, part numbers, and NIOSH testing and certification approval (TC) numbers of all items tested are provided in the online Supplementary Materials.

NIOSH, National Institute for Occupational Safety and Health; *HEPA*, high-efficiency particulate air; *PAPR*, powered air-purifying respirator.

* The efficiency of the HEPA filtration panel for filtering exhalated breath was not evaluated as part of the NIOSH approval process. The HEPA filtration panel functions for source control purposes and the NIOSH approval process evaluates for respiratory protection purposes.