Title: Efficacy of powered air purifying respirators (PAPRs) as source control devices for simulated respiratory aerosols—Materials and Methods

Dataset Number:

Materials and Methods

Respiratory aerosol simulator

The experiments were done using an i-Bodi head-and-torso manikin (Crawley Creatures, Ltd.) in an acrylic enclosure (Figure 1). The manikin head corresponds to the ISO medium standard headform[1] and has a 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.[2]A schematic of the aerosol flow is shown in Figure 2. The respiratory simulator was operated with a breathing rate of 12 breaths/minute and a ventilation rate of 15 liters/minute, which is the ISO standard ventilation rate for a woman performing light work.[3]

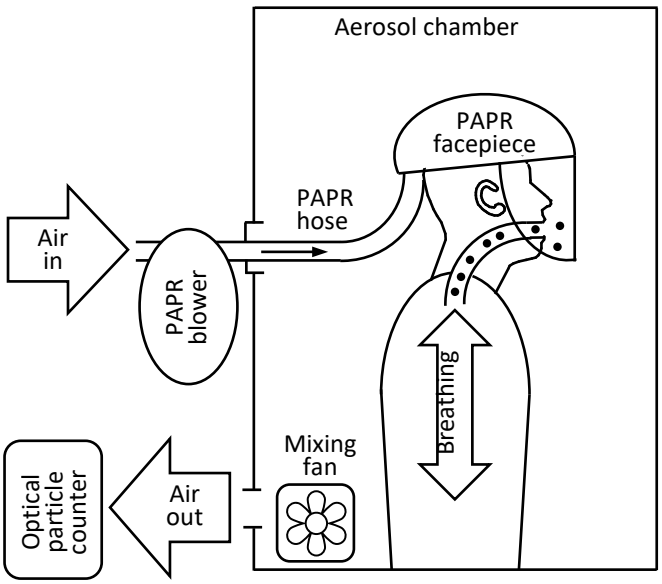

Figure 1: Experimental set-up for source control experiments.

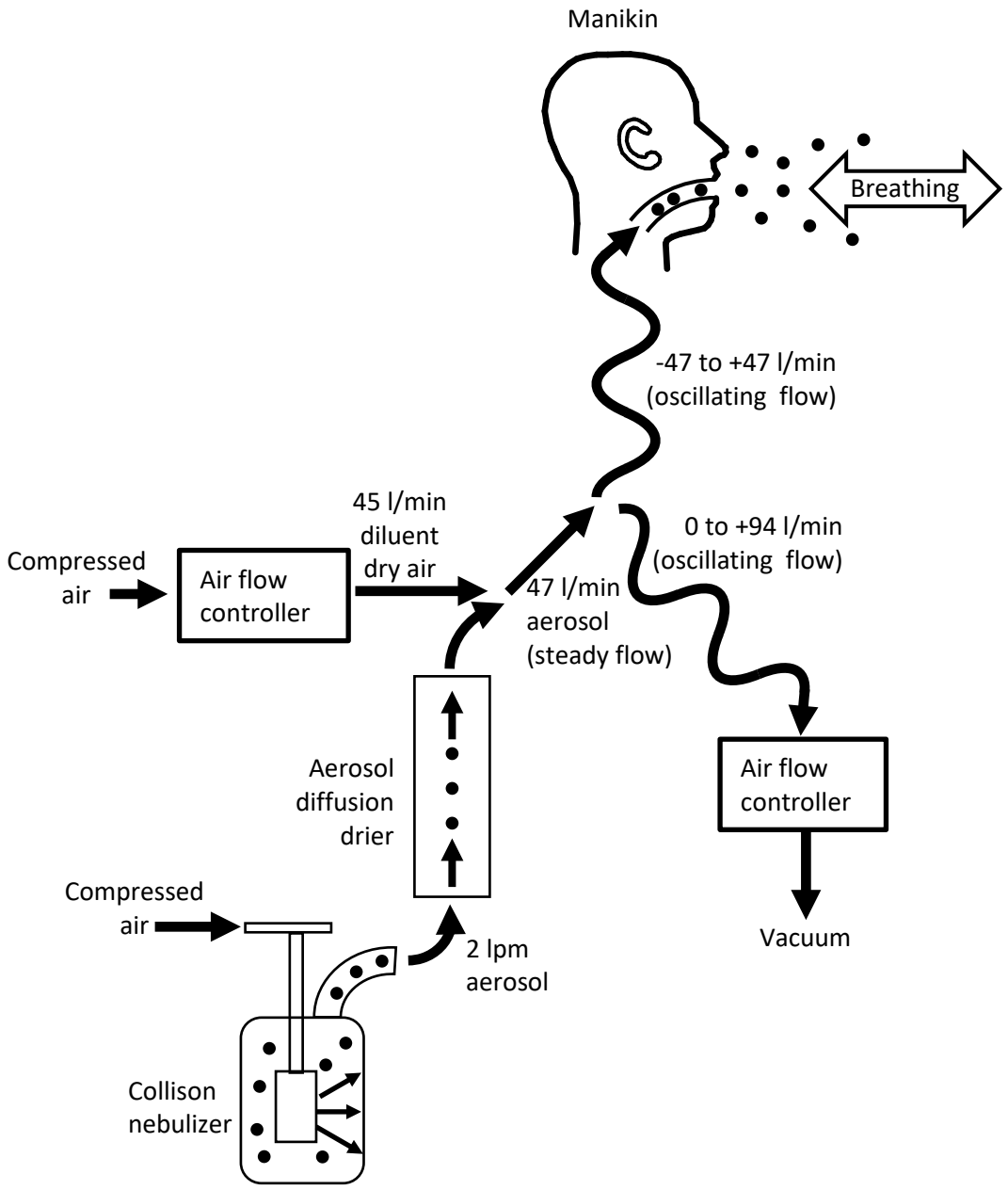

Figure 2: Schematic of aerosol flow through respiratory aerosol simulator. The respiratory aerosol was produced using a 5% KCl solution in a Collison nebulizer operating at 138 kPa (20 lbs./in^2), dried using a diffusion drier (Model 3062, TSI), and neutralized using a bipolar ionizer (not shown; Model HPX-1, Electrostatics). One mass flow controller was connected to a source of clean dry pressurized air and provided a steady airflow that mixed with the neutralized aerosol to give a constant airflow of 47 liters/minute with a constant aerosol concentration. The second mass flow controller was connected to a vacuum source and provided a sinusoidal return flow oscillating between 0 and 94 liters/minute. The two mass flow controllers were connected with a wye-fitting near the mouth of the manikin so that the net combined airflow at the mouth of the manikin oscillated approximately sinusoidally between -47 and +47 liters/minute. The sinusoidal flow with a peak flowrate of 47 liters/minute and a breathing rate

of 12 breaths/minute corresponded to a ventilation rate of 15 liters/minute, which is the ISO standard ventilation rate for a woman performing light work. This scheme using two mass flow controllers was adopted because it maintains a consistent concentration of the exhaled aerosol over the breathing cycle.

Aerosol collection chamber

The collection chamber for the exhaled aerosol was an acrylic enclosure that measured 68 cm x 68 cm x 94 cm high (27" x 27" x 37") on the inside (Figure 1). The interior of the enclosure was wiped down with anti-static solution (Staticide #2010, ACL Staticide) before starting the experiments. 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. The concentration of the aerosol exiting the chamber was measured using an optical particle spectrometer (Model 3330, TSI). A blower with a HEPA filter was used to purge the chamber between experiments.

PAPRs

Four models of PAPRs and five facepieces from four manufacturers were tested during these experiments (Table 1). Each facepiece was tested while the manikin wore no mask, a tie-on surgical mask (Medicom AssureMask Precision), or an N95 respirator (3M model 9210). Each PAPR was also tested with the blower running but without a facepiece to provide a control condition to allow comparisons of the concentrations of respiratory aerosol particles exhaled by the simulator.
For the Salus, Versaflo, and Sentinel PAPRs, the blower of the PAPR to be tested was placed outside the chamber with the connecting hose passing through the chamber wall and connecting to the facepiece so that the PAPR blower drew air from outside the chamber and exhausted it inside (Figure 1). Since the respiratory aerosol simulator provided no net airflow into or out of the chamber, the airflow through the chamber during experiments was provided solely by the PAPR blower.

Unlike the other PAPRs, the Maxair PAPR has its blower built into the helmet worn by the user; thus, it was not possible to locate the blower outside the chamber. Instead, the top of the helmet (called the filter cover cap) was modified by adding a large port to the back and blocking off the circumferential slit through which air was normally drawn during operation. The port was connected to the opening in the chamber using a flexible hose so that air was drawn from outside the chamber, flowed through the PAPR helmet and filter, and then flowed into the chamber in a similar manner to the other PAPRs. Photographs of the modifications made to the PAPR are shown in the online supplemental materials.

Table 1: PAPRs and facepieces used in study. 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.

Manufacturer	*PAPR*	*Airflow (liters /min)*	*Facepiece*	*Designed to provide source control?*	*PPE used*

3M	Versaflo	185	Medium/large facepiece	No	None Surgical mask N95 respirator
Bullard	Salus HC-M	215	Medium/large hood	No	None Surgical mask N95 respirator
			Small/medium HEPA hood	Yes	None Surgical mask N95 respirator
ILC Dover	Sentinel XP HP	230	Single-sized facepiece	No	None Surgical mask N95 respirator
Syntech International	Maxair	215	Helmet with medium/large lens cuff	No	None Surgical mask N95 respirator

Experimental procedure

For each experiment, a mask or respirator (if needed) was placed on the manikin followed by the PAPR facepiece to be tested. The door of the chamber was then sealed, the OPC began collecting aerosol concentration data, and the chamber was purged with HEPA filtered air for 10 minutes. The final 15 seconds of OPC data collected during the purge was 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 PPE 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 three times (once with no PPE, once with a surgical mask, and once with an N95), except for the Sentinel facepieces, which were reused six times. The N95 respirators were reused four times, while the surgical masks were discarded after a single use to avoid untying and retying the masks.

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 (that is, provided source control), then the concentration would be correspondingly reduced. Because the concentration required 8-10 minutes to reach an equilibrium value, the first 10 minutes of aerosol concentration 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 data from the OPC by the volume of an individual particle based on the volume-weighted mean diameter of the size bin (assuming the particles were spherical) and by 1.984 g/cm^3 (the density of 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 source control performance, or source control collection efficiency, of a device 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.[4] 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%. The performance of each source control device was evaluated by calculating the collection efficiency as:

$$Collection\ efficiency = 1 - \frac{M_{device}}{M_{control}} \qquad (1)$$

Where:
M_{device} = average total mass concentration when testing the source control device.
$M_{control}$ = average total mass concentration while not wearing a source control device.

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

References

1. ISO. ISO 16900-5:2016(E) Respiratory protective devices — Methods of test and test equipment — Part 5: Breathing machine, metabolic simulator, RPD headforms and torso, tools and verification tools. Geneva, Switzerland: International Organization for Standardization, 2016.
2. Li L, Pope ZC, Son Y, Eilts SM, Hogan CJ, Kong M. Effects of portable air filtration on submicrometer- and micrometer-sized particle deposition and concentration in a natural ventilated skilled nursing facility. Build Environ. 2023;240:110454. doi: 10.1016/j.buildenv.2023.110454
3. ISO. ISO/TS 16976-1:2015 Respiratory protective devices -- Human factors -- Part 1: Metabolic rates and respiratory flow rates. Geneva, Switzerland: International Organization for Standardization, 2015.
4. Lindsley WG, Blachere FM, Beezhold DH, Law BF, Derk RC, Hettick JM, et al. A comparison of performance metrics for cloth masks as source control devices for simulated cough and exhalation aerosols. Aerosol Sci Technol. 2021;55:1125-42. doi: 10.1080/02786826.2021.1933377