Title: Constant vs. cyclic flow when testing face masks and respirators as source control devices for simulated respiratory aerosols--Dataset

Dataset Number:

Materials & methods

Summary

A source control measurement system was used to measure the efficacy of two cloth face masks, two medical masks with and without an elastic mask brace, a neck gaiter, and an N95 respirator as source control devices for simulated respiratory aerosols. With this system, the aerosol flows from the inside of the mask toward the outside; that is, the aerosol flows in the same direction as it would flow during an exhalation by a person wearing the source control device. The experiments were conducted under four airflow conditions: cyclic breathing at 15 liters/minute (L/min), cyclic breathing at 85 L/min, constant outward airflow at 15 L/min, and constant outward airflow at 85 L/min. Each experiment began by placing the source control device on the headform and performing a fit test. The measurement system collection chamber was then sealed, and the cyclic or constant airflow and the aerosol generation were initiated. The aerosol concentration in the collection chamber was measured using an optical particle spectrometer (OPS). The source control collection efficiency was determined by comparing the steady-state concentration of aerosol particles in the collection chamber when the source control device was worn with the concentration when no source control device was used.

Source control devices

In this study, “cloth mask” refers to a face mask constructed from woven or knitted textiles that is not a surgical mask or respirator. A “neck gaiter” is a knitted fabric tube that encircles the head and neck. “Medical mask” refers to a disposable mask made of non-woven polymer textiles that is held on the face with elastic ear loops. Commercial manufacturers often refer to medical masks held on by ear loops as procedure masks and masks that tie behind the head as surgical masks. However, the U.S. Food and Drug Administration uses the term “surgical mask” to describe all types of masks regulated under 21 Code of Federal Regulations (CFR) 878.4040 for performing medical procedures (FDA 2004). Cloth masks, neck gaiters, and medical masks typically fit loosely and will not necessarily protect the wearer from aerosol particles. A “respirator”, such as an N95 filtering facepiece respirator, is a personal protective device that is constructed of materials with a high filtration efficiency and that is designed to fit tightly to the face. A respirator is designed to protect the wearer from airborne particulate matter when it is properly fitted. In the United States, respirators must be approved by the National Institute for Occupational Safety and Health (NIOSH) under 42 CFR Part 84 (NIOSH 1995).

For this study, two medical masks, two cloth masks, one neck gaiter and one N95 respirator were selected to provide a range of source control collection efficiencies. For the source control tests, each device was placed on the headform as it would normally be worn by a person. The neck gaiter was folded over to provide two layers of fabric. The medical masks were tested both as normally worn and

with an elastic mask brace (Fix the Mask, FTM Corporation) placed over the perimeter of the medical mask to reduce face seal leakage and improve the source control performance (Blachere et al. 2022).

Before the source control test, the manikin fit factor (Janssen and McKay 2017) was measured by performing a respirator fit test (Bergman et al. 2015) for each device using a PortaCount® Pro+ respirator fit tester (Model 8038, TSI, Shoreview, MN). The PortaCount was used in Class 100 mode (also called N99 mode), in which the tester measures the concentration of aerosol particles from 0.02 to 1.0 μm at the mouth of the headform (inside the source control device) and in the ambient air (outside the device) (TSI 2010). The aerosol was generated using a 1% KCl solution in a medical nebulizer (Hospitak Up-Mist, Unomedical) at 34 kPa (5 lbs./in^2) air pressure. Aerosol samples at the mouth of the headform were collected through a sampling port in the headform; thus, it was not necessary to install a sample port in the source control device as is done when performing fit tests with people. Fit tests were performed with the system cyclically breathing at 36 L/min. The fit factor (FF) was calculated as (Janssen and McKay 2017; TSI 2015):

$$FF = \frac{C_B + C_A}{2C_R}$$

Where:

C_B = particle concentration in an ambient aerosol sample collected before the mask sample was taken.

C_A = particle concentration in an ambient aerosol sample collected after the mask sample was taken.

C_R = particle concentration in the aerosol sample collected at the mouth inside the source control device.

To allow a direct comparison between the source control collection efficiency and the fit, the fit factor was transformed to the fit efficiency (FE) by the formula FE = 1 - 1/FF.

Respiratory aerosol source control measurement system

The effectiveness of source control devices at blocking aerosols produced during cyclic breathing and constant airflow exhalation were determined using a modified version of the custom-built respiratory aerosol source control measurement system described previously (Lindsley et al. 2021a; Lindsley et al. 2021b). The differences between the previous system and the current one are explained in detail in the online supplemental materials. The system includes a breathing aerosol simulator, a manikin headform, a 136 L aerosol collection chamber, and an optical particle spectrometer (OPS; Model 3330, TSI) to measure the aerosol concentration. The manikin headform (Hanson Robotics, Plano, TX) used in the study has pliable skin that mimics the elastic properties of human skin in order to create a realistic simulation of how each source control device would fit a human face (Bergman et al. 2014).

The test aerosol was produced using a solution of 1% potassium chloride (KCl) in a single-jet Collison nebulizer (BGI, Butler, NJ, USA) at 69 kPa (10 lbs./in^2), which produced a flowrate of 1.5 L/min. The aerosol passed through a diffusion drier (Model 3062, TSI), mixed with dry filtered air (diluent air), and was neutralized using a bipolar ionizer (Model HPX-1, Electrostatics, Hatfield, PA).

For the cyclic breathing tests, the 1.5 L/min of aerosol was mixed with 13.5 L/min of diluent air, and the 15 L/min diluted aerosol then flowed into the elastomeric bellows. The bellows was driven by a linear motor to produce the 15 or 85 L/min sinusoidal breathing pattern. A vacuum scavenger port near the mouth of the headform withdrew 15 L/min of air to balance the 15 L/min input so that the airflow in and out of the mouth was due only to the inhalation and exhalation produced by the bellows (that is, the system had a net airflow of zero from the mouth over a complete inhalation-exhalation cycle). A vacuum line with a filter removed 91 L/min of air at the base of the chamber (an additional 1 L/min was drawn by the optical particle spectrometer described below for a total of 92 L/min). Room air was passively drawn into the collection chamber through one-way air valves above the headform to balance the airflow. In addition, the lower section of the collection chamber had a neoprene rubber wall that was able to flex in and out when the exhalation airflow exceeded the rate of air removal so that air was not forced out of the chamber.

For the 15 L/min constant airflow tests, 15 L/min of diluted aerosol flowed into the elastomeric bellows. However, the bellows was kept compressed and stationary during the experiments and the vacuum scavenger at the mouth was not used. Thus, there was a constant 15 L/min airflow out of the mouth of the headform during the test. Similarly, for the 85 L/min constant airflow tests, the 1.5 L/min of aerosol from the nebulizer was mixed with 41 L/min of diluent air, and the 42.5 L/min of diluted aerosol then flowed into the bellows. An additional 42.5 L/min of diluent air was introduced into the bellows through a separate port and mixed with the diluted aerosol to give a total of 85 L/min outward airflow from the mouth. As with the cyclic breathing experiments, a vacuum line with a filter removed 91 L/min of air at the base of the chamber and the airflow was balanced by drawing in room air through one-way valves at the top of the chamber.

During the experiments, an optical particle spectrometer (OPS; Model 3330, TSI) at the bottom of the collection chamber measured the aerosol concentration by continuously drawing an aerosol sample out of the collection chamber at 1 L/min. The OPS reported the aerosol particle number concentration (# particles/cm^3) at 1 Hz in 16 logarithmically spaced size bins from 0.3 to 10 µm. Since the OPS only measured a sample of the total aerosol in the chamber, a small fan was added to the chamber below the mouth of the headform to mix the aerosol coming from the headform with the air in the chamber.

Source control collection efficiency measurement

After the source control device was placed on the headform and the fit test was performed, each experiment began by measuring the background aerosol concentration inside the collection chamber for 15 seconds. The cyclic breathing or constant airflow and the aerosol generation were then initiated and continued for 20 minutes. The control experiments with no source control device indicated that the aerosol concentration reached a steady-state in 8.2 minutes or less (data not shown), so the data from the first 10 minutes of operation was not used and the steady-state concentration was calculated based on the average concentration during the second 10 minutes of operation minus the background aerosol concentration. The particle concentration data was checked to verify that the chamber aerosol concentration did not exceed 3000 particles/cm^3, which is the upper concentration limit for the OPS.

Filtration efficiency and airflow resistance measurements

The filtration efficiency of the source control device is the fraction of the test aerosol that is collected as the aerosol passes through the device material. For example, if 70% of the test aerosol is collected by the device material and 30% of the aerosol passes through it, then the filtration efficiency is 70%. The source control device was sealed to a fixture during the filtration efficiency tests. Thus, the filtration efficiency is a property of the mask material and does not include any effects of leaks between the edge of the mask and the face of the wearer (face seal leakage).

The filtration efficiency and airflow resistance were measured using automated filter testers (Models 8130 and 8130A, TSI). Material samples were secured to a test plate using beeswax. Measurements were made using a modified version of the NIOSH standard testing procedure (STP) (NIOSH 2019). Under the modified STP, samples were tested at ambient temperature and humidity but were not subjected to conditioning at 38° C and 85% relative humidity for 25 hours, and sample testing was limited to 10 minutes. The device to be tested was oriented in the filter tester so that the air and aerosol flowed from the exterior of the device toward the interior (that is, as if the wearer were inhaling, which is the same direction as when testing a respirator as a personal protective device). The challenge aerosol was generated using a 2% sodium chloride (NaCl) solution in distilled water, conditioned to 25°C and 30% relative humidity and neutralized to the Boltzmann equilibrium state. The challenge aerosol had a count median diameter of 75 nm ± 20 nm, a mass mean diameter of 260 nm and a geometric standard deviation (GSD) ≤ 1.86 (TSI 8130A specifications). The automated filter tester compares particle mass concentration readings from upstream and downstream using light-scattering laser photometers to calculate the material filtration efficiency. An electronic pressure transducer measures the pressure difference across the material sample to indicate airflow resistance. Tests were performed with a constant airflow of 85 L/min.

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