Title: Efficacy of Do-It-Yourself Air Filtration Units in Reducing Exposure to Simulated Respiratory Aerosols_Dataset

MATERIALS AND METHODS

2.1 Mock Classroom Layout and Room Ventilation

A conference room was used as the mock classroom for these experiments. It measured 6.6 m wide by 9.1 m long with a height from floor to ceiling of 3 m. The airflow to the room originated from the building's Air Handling Unit (AHU) which mixes return air with fresh outside air. The AHU that supplies air to the room is a large system serving multiple areas. The total supply air passed through a set of prefilters (HC MERV 10 Pleated Air Filter; Filtration Group; Mesa, AZ) and a MERV 13 V-Bank filter (DuraMAX 4v; Koch Filter Corporation; Louisville, KY) before being supplied to the room through six 0.6 m x 1.2 m slot diffusers, all controlled by the same variable-air-volume (VAV) box. The slot diffusers were evenly distributed with three diffusers along each longitudinal wall. The return air entered the ceiling plenum through three 0.6 m x 1.2 m diffusers located through the midline of the room (See Mock classroom layout diagram).

2.2 HVAC Clearance Rates

The HVAC system clearance rates were determined using three methods: an HVAC measurement/calculation method based on the measured total HVAC clean air supply rate (because the room was under positive pressure the supply air was measured instead of the return air), a tracer gas decay method using sulfur hexafluoride tracer gas, and an aerosol decay method using potassium chloride (KCl) aerosols.

HVAC measurement/calculation method determined the HVAC supply rates at each of the six supply inlets by measuring with an Alnor Balometer with a 0.6 m x 1.2 m Capture Hood (Model EBT731; TSI Corporation) and summed. This air supply rate was divided by the volume of the meeting room to estimate the air volume displacement rate, expressed as air changes per hour (ACH).

Tracer gas decay measurements collected from within the room's occupiable space. Four Innova Photoacoustic Infrared Spectroscopy Analyzer models 1412, 1412i(2x) and 1512 (California Analytical Instruments, Inc., Orange, CA), were placed throughout the meeting room. All units were equipped with sulfur hexafluoride (SF6)-specific optical filters. The SF6 tracer gas (99.8% purity; Scott Specialty Gases, Inc., Plumsteadville, PA) was released into the meeting room and allowed to mix to a target concentration of approximately 10 ppm. Mixing was aided by one 12" diameter desktop vane axial fan and one larger 24" diameter pedestal-base vane axial fan, in addition to the HVAC system ventilation. The fans were then turned off, and SF6 concentrations were continuously measured at a sample frequency of approximately 1.2 – 1.5 samples/min (each instrument was slightly different) for at least 30 minutes to document the decay rate at each of the four sample positions. After each test, the four analyzers were randomly shuffled among the four analyzer locations to reduce the potential impact of any instrument bias. Since the tracer gas could be recirculated by the AHU (although it was highly diluted), a concentration of 50 ppb SF6 was considered an acceptable background concentration prior to initiating the next test. The SF6 concentration decay for the four analyzers were individually plotted as a simple exponential decay using Microsoft Excel (Redmond, WA). The slope of each decay curve represented the air exchange rate for each instrument location. The tracer gas-based overall room effective ACH was determined by averaging the four localized air exchange rates.

The aerosol concentration decay method (similar to the tracer gas decay method) was used to determine an effective ACH rate. The meeting room was dosed with aerosols from a 14% KCl solution atomized using a 3-jet Collison jet atomizer for 20 minutes; a 24" diameter pedestal-base vane axial fan provided mixing prior to aerosol measurement. Aerosol concentrations were quantitated for a minimum of 20 minutes during the aerosol decay phase using eight symmetrically spaced optical particle counters (Model 3330, TSI Corp.) throughout the room – each sampling at 1 second intervals. Particle counts for the three measurement size bins :0.3 to 0.4 µm, 0.4-0.5 µm, and 0.5-0.65 µm, were aggregated together for each instrument and plotted as a simple exponential decay using the R statistical environment v. 4.0.2 (R Project for Statistical Computing; Vienna, Austria). The slope of each decay curve represented the air exchange rate for each OPC location and was averaged among all OPCs for the particle-based overall room airflow rate.

All experiments were conducted with the room HVAC system and VAV box set to provide a constant 2 ACH.

2.3 Breathing Simulators and Masking

To examine the efficacy of the DIY air filtration units in reducing exposure to potentially infectious respiratory aerosols, one aerosol-producing Source breathing simulator and three Recipient breathing simulators were positioned to simulate a mock classroom (or lecture) setting. The Source and Recipient simulators have been described in detail previously. The respiratory aerosol source simulator simulated a person who was exhaling aerosol particles into the room. The test aerosol was produced using a solution of 14% potassium chloride (KCl) in a single-jet Collison nebulizer (BGI, Butler, NJ) at 103 kPa (15 lbs./in^2). The aerosol passed through a diffusion drier (Model 3062, TSI, Shoreview, MN), mixed with dry filtered air and was neutralized using a bipolar ionizer (Model HPX-1, Electrostatics). The aerosol mixing occurred in an elastomeric bellows which served as the mixing chamber and simulated lung of the Source simulator. During the experiments, the nebulizer was continuously cycled 20 seconds on and 40 seconds off to prevent the aerosol concentration in the room from exceeding the upper concentration limit of the aerosol particle counters.

Each of the three Recipient simulators was equipped with an optical particle counter (OPC; Model 1.108; Grimm Technologies, Inc.; Douglasville, GA, USA) connected to a stainless-steel sampling tube extending from the back of the head to an opening directly adjacent to the mouth, which measured the exposure to the simulated respiratory aerosols. The OPCs had a size measurement range of 0.3-3.0 μm with a sampling frequency of 1 Hertz. The sampling tube was located such that, when a mask was worn by the simulator, the sampling tube was under the mask. One Recipient simulator representing a teacher or speaker (called Recipient C) was positioned in a standing height near the front of the room with the mouth position and OPC sampling tube 152 cm from the floor. Recipient C was positioned near the midline of the room and between the intake slot vents in the ceiling. The Source was positioned within the foremost row of the audience/participant area in a sitting position and 1.8 m directly in front of Recipient C with the month center 101 cm from the floor. Recipients A and B were adjacent to the Source simulator, with A positioned 0.9 m to the left of and B positioned 1.8 m to the right and with the mouth and OPC sampling tube positioned 101 cm from the floor.

All Source and Recipient simulator head forms were covered with a synthetic elastomer to simulate the pliability and texture of human skin. The simulator head forms did not include nostril openings. The Source head form was from Hanson Robotics (Plano, Texas, USA), while Recipient head forms were from Crawley Creatures Ltd (Model: Respirator Testing Head Form 1; Buckingham, UK). The Source and Recipient A and B simulators breathed using a computer-controlled linear motor affixed to elastomeric bellows to simulate lungs. The breathing cadence was calibrated to a tidal volume of 1.25 liters/breath and 12 breaths/minute with a minute ventilation rate of 15 liters/minute corresponding to the ISO standard for females performing light work [39]. Recipient C breathed using a commercial respiratory simulator (Warwick Technologies Ltd., Warwick, UK) with a sinusoidal breathing waveform calibrated to 21.5 breaths/minute with a minute ventilation rate of 26 liters/minute, which is approximately the average of the ISO standards for males and females engaged in moderate work [39].

Face masks were 3-ply cotton cloth masks with ear loops (Defender; HanesBrands Inc.; Winston-Salem, NC, USA). Experiments were conducted with all simulators either unmasked or masked (universal masking). Mask fit was determined using the PortaCount Pro+ (Model 8038; TSI Corporation; Shoreview, MN) in N99 mode as per manufacturer’s instructions.

2.4 Box Fan Specifications

Seven new 51 cm (20”) box style fans were evaluated: Air King model 4CH71G/9723G, Lasko model B20200, Lasko Premium model 3723, Comfort Zone model CZ200A, Pelonis model FB50-16H, Genesis model G20BOX-WHT, and Hurricane model HGC736501. All fans were listed as residential fans except for the Air King which was labeled as a commercial grade fan. To increase the efficiency of each fan, a shroud made of duct (see DIY diagram) was attached to the corners of the fan chassis that extended beyond the end of the fan blades on the outflow side of the fan. The following performance parameters were evaluated for each fan while running at high and low speeds: airflow in cubic feet per minute (CFM), noise in decibels (dB), fan current (ampere), fan power (Watts) and fan blade revolutions per minute (RPM). Parameters were measured on the shrouded fan alone and two configurations of DIY air filtration units with 2.5 and 5 cm filters. Descriptions of the two DIY air filtration unit configurations are described in the methods and materials and illustrated in Figure 1. Fans were allowed to operate for at least one minute prior to acquiring all measurements to achieve full operational speed.

The airflow for each fan was determined using an Alnor® LoFlo Balometer® with a 0.6 m × 0.6 m Capture Hood (Model EBT731, TSI Corporation). A 70 x 70 cm piece of double strength cardboard with a 50 cm hole was positioned on top of the fan with the hole centered over the fan blades to avoid any interference with airflow. The balometer was then placed on top of cardboard and the airflow was measured.

A real-time octave band analyzer (Extech model 407790, Extech/FLIR Systems, Nashua, NH) was used to measure the decibel A scale (dBA) levels of the fans and DIY units placed in the same location at the front of the room. The room HVAC system was set at a constant 2 ACH for all noise measurements and all doors were closed to the room. To minimize location effects of the DIY units on noise, equivalent continuous sound pressure level (L_{eq}) measurements for 5 seconds were acquired at the eight OPC locations and then averaged together for a room mean noise level. This procedure was used to obtain a background noise level with the HVAC system set at 2 ACH and no DIY units operating. Additionally, noise levels were measured for DIY air filtration cubes operating simultaneously in the front and back of the room constructed with the Air King and Comfort Zone fans with both 2.5 and 5 cm filters.

Electrical current measurements were obtained by plugging the fan’s electrical cord into a line splitter and measuring current using a digital Volt multimeter (Fluke Model 189, Fluke Corporation, Everett, WA) with an AC current clamp (Fluke Model i800). Prior to turning the fan on to take measurements, the current clamp was placed on the line splitter to obtain a background current reading, which was subtracted for the operating reading. The voltage of the electrical outlet was measured with the multimeter prior to taking current measurements. Fan power in Watts was determined by the Watts Law Formula; $P=V*C$ (P is power in Watts, V is voltage in Volts and C is current in Amperes). The fan blade rotation rate was measured with a non-contact optical tachometer (Monarch model PT99, Monarch Instrument, Amherst, NH).

2.5 Description of DIY Air Filtration Units

The DIY air filtration units were assembled using 51 x 51 cm (20” x 20”) MERV 13 Air Handler filters (W.W. Grainger, Inc., Lake Forest, IL) that were either 2.5 or 5 cm thick (Supplemental Table S1 – Filter Specifications). The MERV rating is a performance rating for HVAC filters based on ANSI/ASHRAE Standard 52.2-2017, with higher numbers indicating higher filtration efficiencies. A MERV 13 rating means that the filter removes ≥50% of aerosol particles with a diameter of 0.3 to 1 μm, ≥85% of 1 to 3 μm particles, and ≥90% of 3 to 10 μm particles. MERV 13 filters were selected because, early in the COVID-19 pandemic, ASHRAE recommended that HVAC filters in non-healthcare facilities be upgraded to MERV 13 filters if possible, or otherwise to the highest rated filter an HVAC system can accommodate.

Two brands of box fans, the Air King (model 4CH71G/9723G) and Comfort Zone (model CZ200A), were each used to construct the two configurations of DIY units, yielding four different DIY unit configurations. The first two unit configurations were a modified version of the Ford/Lasko DIY air filtration unit (DIY Diagram A) with either a 2.5 cm filter (configuration 1) or 5 cm filter (configuration 2) [34]. The design was modified by increasing the length of the feet of the cardboard holder to give a total height of 61 cm and orienting the filter and fan, so the direction of airflow was upwards to place the fan at the same height and airflow direction as the DIY air filtration cubes. The original Ford kits were supplied with 10 cm thick filters, but this study used 2.5 and 5 cm filters because they are more widely available. The third and fourth configurations were DIY air filtration cubes (DIY Diagram B) built with four filters that were either 2.5 cm thick (configuration 3) or 5 cm thick (configuration 4). Four filters were used so that the units could be placed directly on the floor on a cardboard base. The filters were orientated with the filter directional airflow arrows pointed inward so that the direction of airflow was inward through the filters. The units were taped together along the entire edge of the filters with duct tape (Gorilla Heavy Duty Black, 603560) and a 51 cm x 51 cm cardboard base was taped to the bottom of the filters. The box fan was taped to the top of the cube along all edges with the direction of airflow upwards. All gaps between filters/fan and any holes in the fan chassis were sealed with duct tape to ensure air was drawn through the filters and not bypassing the filters through leaks.

2.6 Aerosol clearance Rates using the DIY Air Filtration Units

The aerosol concentration decay method was used to determine the effective air changes per hour (ACH) for each DIY air filtration unit. Using a 3-jet Collison nebulizer, the meeting room was dosed with aerosols from a 14% KCl solution in distilled water for 20 min. A 64 cm diameter pedestal-base vane axial fan provided mixing prior to aerosol measurement. Aerosol concentrations were quantitated for a minimum of 20 min during the aerosol decay phase. To measure aerosol concentrations, eight OPCs (Model 3330, TSI Corp.) were symmetrically placed in the room at a height of 101 cm corresponding to the sitting height used in this study. The OPCs sampled at 1 second intervals and were set to measure aerosol particle number concentrations in three size bins: 0.3-0.4 μm, 0.4-0.5 μm, and 0.5-0.65 μm. The bins were aggregated together for each instrument and fit with an exponential decay curve using the R statistical environment v. 4.0.2 (R Project for Statistical Computing; Vienna, Austria). The slope of each decay curve was then used to derive the aerosol concentration decay rate to calculate the air exchange rate. Since the air change rate used here is not a traditional air exchange where all air is removed from the room by way of the HVAC system but included both the HVAC system and air filtration through the DIY units, it will be described as an effective air change rate. Effective air change rates were calculated for each of the eight OPCs and then averaged to calculate the mean effective air change rate for each experimental condition.

2.7 Test Procedure and Aerosol Measurement

At the start of each test run, residual particles were cleared by increasing the HVAC system ventilation rate to maximum and observing the aerosol concentration over time. When a plateau was reached, the room HVAC system was set to 2 ACH and the DIY air filtration unit(s) turned on for a minimum of 5 minutes to reach a steady-state airflow pattern. Recipient simulators were also activated to initiate the breathing cycles, while OPC sampling was started to collect the background particle concentrations. At test time zero, the Source simulator was activated to breathe with a sinusoidal waveform of 15 L/min continuously throughout the experiment. Aerosols were generated using a single jet Collison atomizer filled with 14% w/v KCl in distilled water, with a cadence of 20 seconds aerosol generation followed by 40 seconds of no aerosol; the aerosols were produced throughout the 60-minute duration of the experiment. Each experimental condition was performed in quadruplicate.

The room temperature and humidity were monitored in real-time using a temperature and relative humidity probe and data logger (Vaisala Oyj; Vantaa, Finland). Barometric pressure was reported by each TSI OPC.

2.8 Data Processing

Size-binned particle count data and elapsed time reported by each Grimm and Model 3330 OPC were processed using the R Statistical Environment v. 4.0.5 (R Project for Statistical Computing; Vienna, Austria). Bin-specific particle counts for the 180 seconds preceding the start of aerosol generation were used to estimate the background aerosol concentration, which were then subtracted from OPC particle counts. The mass concentration of aerosol (µg/m^3) per size bin was calculated by multiplying the bin-specific particle count by the volume of the bin-specific median diameter (assuming the particles were spherical) and then multiplying by 1.984 g/cm^3 (density of KCl). Note that this conversion from particle counts to particle mass is commonly used but is an approximation. For each OPC, the bin-specific background-corrected aerosol mass concentration was summed across all bins to derive a total aerosol mass concentration per time point. The aerosol mass concentration throughout the experiment was averaged to determine the mean aerosol mass concentration (mean aerosol exposure) which served as the exposure metric for the investigation for each Recipient.

2.9 Spatial Mean Mass Concentration Distribution

Area samples measured from the Model 3330 OPCs were used to generate 2D rasterized overlays of mean mass aerosol concentration. Spatial overlays were performed by inverse distance weight modeling with the "gstat" package in R. First, a grid of evenly spaced points throughout the exposure plane was constructed, over which predicted OPC mean mass concentrations were fitted from the observed data. The mean mass concentration range was fixed between 2.9 µg/m3 and ≥28 µg/m3. Values greater than 28 µg/m3 were colorized analogous to the maximum value to increase resolution at the lower concentrations.

Abbreviations

ACH: Air change per hour; AHU: Air handling unit; OPC: Optical particle counter; HVAC: Heating ventilation, and air conditioning; KCl: Potassium chloride; DIY: Do-It-Yourself: MERV; minimum efficiency reporting value

Mock Classroom Layout Diagram