

**Title:** Efficacy of ventilation, HEPA air cleaners, universal masking, and physical distancing for reducing exposure to simulated exhaled aerosols in a meeting room

**Dataset Number:** RD-1025-2021-0

## **Methods**

### *Simulators, Masking, and Aerosol Measurement*

To better understand the effects of physical distancing, masking, and ventilation, experimentation was conducted simulating a classroom-style meeting room setup with a speaker being positioned at the front of the room and multiple participants. Each experiment simulates a scenario of one respiratory aerosol simulator (Source) as an infected individual and three noninfected breathing simulators (Recipients). The distance from floor to mouth of the breathing simulator at the speaker's position was 152 cm to simulate an adult standing, while the mouths of the participant breathing simulators were 102 cm from the floor. Four different scenarios of the simulators were examined. For an additional position scenario, Recipient C was repositioned into the audience and the Source simulator was placed in the speaker position.

Recipient C was purchased from Warwick Technologies Ltd. (Warwick, UK) while the remaining simulators (Source and Recipients A and B) were custom-built. The Source simulator headform was purchased from Hanson Robotics (Plano, TX) while Recipients A and B simulator headforms were from Crawley Creatures Ltd. (Model: Respirator Testing Head Form 1; Buckingham, UK); all simulator headforms were composed of a shell of elastomer to mimic human skin.

The Recipient C used a sinusoidal breathing waveform with a respiration rate of 21.5 breaths/minute and a ventilation rate of 27 L/minute, which is approximately the average of the International Organization for Standards (ISO) standards for males and females engaged in moderate work. Participant A and Participant B used an elastomeric bellows controlled by a computer-enabled linear motor and breathed with a constant sinusoidal waveform calibrated to 12 breaths/minute at a tidal volume of 1.25 L/breath, resulting in a breathing ventilation rate of 15 L/minute. The breathing parameters for these two simulators correspond to females performing light work. The aerosol exhaled by the source simulator has a mass median aerodynamic diameter (MMAD) of 1.3  $\mu\text{m}$  with a geometric standard deviation (GSD) of 2.3.

The 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). To assess mask fit, fit factors were determined using the PortaCount Pro+ (Model 8038; TSI Corporation; Shoreview, MN) in N99 mode as per manufacturer's instructions.

To determine the aerosol particle exposure of each Recipient, the concentrations of particles between 0.3 and 3  $\mu\text{m}$  were measured at the mouth of each Recipient using optical particle counters (OPCs) (Model 1.108; Grimm Technologies, Inc.; Douglasville, GA, USA). When the breathing simulators were wearing face masks, the particle counters affixed to the Recipients

collected aerosol samples from inside the masks (i.e., the particle counter measured the concentration of the aerosol being inhaled by the Recipient).

### *Meeting Room Layout and Ventilation*

The meeting room used for experimentation had nominal dimensions of 6.6 m wide by 9.1 m long (with small cut-out areas that subtracted from the floor area) and a height approximately 3 m from floor to ceiling. Considering the cut-out areas, the floor surface area and room volume were 54.3 m<sup>2</sup> and 164.0 m<sup>3</sup>, respectively. Airflow to the meeting room originated from a building air handler unit (AHU) with an economizer and variable frequency drive. The AHU was set to deliver 55 °F supply air to variable-air-volume (VAV) boxes that provide supply air to the meeting room and many other rooms on three floors of the building. The supply air first passed through a set of prefilters (HC MERV 10 Pleated Air Filter; Filtration Group; Mesa, AZ, USA) and then passed through a MERV 13 V-Bank filter (DuraMAX 4v; Koch Filter Corporation; Louisville, KY, USA). For this testing, the controls to the VAV boxes were overridden to ensure a constant airflow rate throughout each test. The air supply entered the meeting room through six 0.6 m × 1.2 m fluorescent light slot diffusers, all controlled by the same VAV box. The slot diffusers were evenly distributed with three diffusers along each longitudinal wall. The return air entered into a ceiling plenum through three 0.6 m × 1.2 m fluorescent light diffusers located through the midline of the room. The meeting room used for testing received less than 4% of the total amount of supply air provided by the AHU. Given this, any effects from air recirculation, as opposed to a 100% single-pass airflow delivery, were negligible to our test methodology and ignored for the purpose of this work.

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 (room was positive pressure so 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.

For the HVAC measurement/calculation method, the HVAC supply rates at each of the six supply inlets were measured using an Anor Balometer with a 0.6 m × 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 ACH.

As an alternative to the HVAC measurement/calculation ACH, an effective ACH (ACH<sub>eff</sub>) was measured using tracer gas decay measurements collected from within the room's occupiable space. Four Innova Photoacoustic Infrared Spectroscopy Analyzer models, 1412, 1412i (2×), and 1512 (California Analytical Instruments Inc.; Orange, CA, USA), were placed throughout the meeting room. All units were equipped with sulfur hexafluoride (SF<sub>6</sub>)-specific optical filters. The SF<sub>6</sub> tracer gas (99.8% purity; Scott Specialty Gases Inc.; Plumsteadville, PA, USA) 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 SF<sub>6</sub> 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 min 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 SF<sub>6</sub> was considered an acceptable background concentration prior to initiating the next test. The SF<sub>6</sub> concentration decays for the four analyzers were individually plotted as a simple exponential decay using Microsoft Excel (Redmond, WA, USA). The slope of each decay curve represented the air exchange rate for each instrument location. The tracer gas-based overall room ACH<sub>eff</sub> was determined by averaging the four localized air exchange rates.

Similar to the tracer gas decay method, the aerosol concentration decay method was also used to determine an ACH<sub>eff</sub> rate. The meeting room was dosed with aerosols from a 14% KCl solution atomized using a 3-jet Collison jet atomizer for 20 min; a 24" 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 using eight symmetrically spaced optical particle counters (Model 3330, TSI Corp.) throughout the room—each sampling at 1 s intervals. Particle counts for the three measurement size bins, 0.3–0.4 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 ACH<sub>eff</sub>.

### *HEPA Air Cleaners*

The HEPA air cleaners were selected using three criteria: (1) units were listed on the Association of Home Appliance Manufacturers (AHAM) certified room air cleaners list; (2) units were readily available to the public from local suppliers or available by purchase online; and (3) units were selected based on the size of the room (including an adjustment for ceiling height above 8') using the clean air delivery rate (CADR) for smoke particles. To augment the HVAC system, two portable HEPA air cleaners (Honeywell 50250-S; Kaz Inc.; Memphis, TN) were placed in various positions throughout the meeting room. This style of unit has a 360° air intake around the sides, draws air through an activated carbon prefilter and then a HEPA filter, and expels air through the top at 360°. Each selected HEPA air cleaner was CADR-smoke rated to provide 0.12 m<sup>3</sup>/s (250 ft<sup>3</sup>/min) of air filtration which corresponded to an equivalent ACH (ACH<sub>equiv</sub>) rate of 2.6. The number of HEPA air cleaners determined for examination was based on meeting or exceeding the clean air delivery rate “2/3 Rule” as recommended by the Environmental Protection Agency. For the size of the meeting room, the minimum recommended total CADR of 0.229 m<sup>3</sup>/s (485 ft<sup>3</sup>/min) was exceeded with two of the selected HEPA air cleaners, which collectively provided a CADR of 0.24 m<sup>3</sup>/s (500 ft<sup>3</sup>/min) on the maximal airflow setting. Experiments using a single HEPA air cleaner were below the recommended CADR but represented scenarios of units not meeting the “2/3 Rule” recommendation.

One or two HEPA air cleaners were placed on the floor of the meeting room, except for the raised configuration in which the HEPAs were placed on 0.8 m high tables. For all HEPA air

cleaner augmentation studies, the HVAC system supply was fixed at 2 ACH which is a ventilation rate representative of office buildings. The  $ACH_{equiv}$  rates of the HEPA augmentation studies were conducted using the KCl aerosol decay rates as described above, yielding a total ACH ( $ACH_{tot}$ ) which reflected the contributions of both the HVAC ACH and the HEPA  $ACH_{equiv}$  for each configuration. A Real Time Octave Band Analyzer (Model 407790; Extech Instrument; Nashua, MA) was used to assess background noise levels during HEPA operation. Noise measurements were taken at the location of the eight area samplers between aerosol testing since the breathing simulators and aerosol source generate significant levels of noise.

### *Test Procedure*

The HVAC system and HEPA air cleaners were run at the test flowrates for approximately 10 min prior to initialization of the Recipient breathing simulators and their personal breathing zone OPC sampling (Grimm samplers). The area samplers (Model 3330 TSI) were initialized concomitantly with the personal breathing zone samplers (colocated at each Recipient breathing simulator location). Background particle concentrations for the three minutes preceding the start of the source aerosol generation were used to determine background aerosol concentrations. At test time zero, the Source breathing simulator was activated and executed the aerosol generation cycle. For these experiments, a 14% w/v solution of KCl in distilled water was nebulized on a 1 min cycle comprising 20 s of constant nebulization via a single jet Collison jet atomizer (BGI Sciences), followed by 40 s without nebulization; this cycle continued for the 60 min duration of the test. The aerosol was passed into the elastomer bellows of the Source that breathed continuously at a rate of 15 L/minute and exhaled through the mouth simulator into the meeting room. At the end of each test, the meeting room doors were opened, the HVAC system was set to 8 ACH, and the HEPA air cleaners were turned on, to reduce particle concentrations back to room baseline prior to starting the next test. Each experimental condition was repeated four times. Ambient conditions were measured using a temperature and relative humidity probe and data logger (Vaisala Oyj; Vantaa, Finland).