

Simulated Workplace Protection Evaluation of a Dual Cavity Respirator Concept

David M. Caretti*, Daniel J. Barker, and Karen M. Coyne

U.S. Army Edgewood Chemical Biological Center, Aberdeen Proving Ground, MD

* Corresponding author & E-mail: david.m.caretti.civ@mail.mil

ABSTRACT

This investigation sought to quantify levels of protection afforded by a single filter dual cavity (DC) respirator concept under simulated workplace conditions. The DC concept included a customized internal fan and a customized nose cup that isolated the nose cup and eye cavity regions within the facepiece. Twelve volunteers completed wear trials of the DC concept and an air-purifying respirator (APR) to quantify levels of protection and subjective feelings of thermal sensation and comfort of each respirator type while performing simulated tactical law enforcement and military personnel tasks. The duration of task performance averaged 31 ± 3 min across all conditions. Methods for continuous reading of in-mask particles with a body-mounted TSI PortaCount® Plus (Model 8020) from freely moving subjects were used to derive simulated workplace protection factors from both the eye (SWPF_{Eye}) and nose (SWPF_{Nose}) regions of the respirator facepiece by dividing ambient by in-mask particle concentrations. All SWPF data were log transformed for analysis. In-mask eye cavity pressures were also recorded continuously during wear of the DC concept. In-mask pressures of the DC concept were not always positive; negative pressures occurred most frequently during performance of the moderate to hard physical tasks. However, average $\text{Log}_{10}\text{SWPF}_{\text{Eye}}$ values did not differ between the APR and DC conditions at any time. Average $\text{Log}_{10}\text{SWPF}_{\text{Nose}}$ were significantly ($p < 0.05$) higher for the DC condition compared to the APR condition during the Fit test (5.44 ± 0.15 vs. 5.21 ± 0.31) and Rifle (5.12 ± 0.22 vs. 4.73 ± 0.89) activities, but lower during the Lift task (4.94 ± 0.49 vs. 5.12 ± 0.21). The DC concept produced cooler thermal sensation ratings than the APR condition across all SWPF tasks; however, statistical differences between conditions were only found during the Crawl and Shovel activities. Subjective ratings of comfort did not differ between DC and APR conditions at any time. The results of this investigation suggest that advantages of a single filter, dual cavity pressurization concept over a properly sized and fitted standard full-facepiece APR were marginal at best when performing simulated tactical operational activities. Additional refinements to the dual cavity pressurization concept are currently being investigated.

Keywords: simulated workplace protection factor, respirator fit, respirator design, comfort

INTRODUCTION

Recent efforts toward enhancing the protective capabilities of full facepiece air-purifying respirators (APRs) led to the concept of the dual cavity respirator system (Pelfry et al., 2010). In brief, the dual cavity concept isolates the positive and negative pressure swing during a breathing cycle within a separate cavity in the respirator (i.e., the nose cup) while using a small amount of positive pressure to purge the outer cavity (i.e., eye region). As such, dual cavity pressurization allows a full-facepiece respirator to be separated into two zones and isolates the nose cup for respiration. This configuration forms a “dead zone” in the space between the nose cup and the facepiece peripheral seal that is pressurized using a small pump, fan or blower positioned inside of the facepiece to achieve a positive pressure. Data provided by Pelfry et al. (2010) suggest that even a small amount of positive pressure can be effective at countering the effects of minor instantaneous leaks in the peripheral mask seal that can occur during vigorous activities or through some external disturbance of the mask. The dual cavity concept promulgated by Pelfry et al. (2010) required two external filtering elements, one dedicated for filtering breathing air and one dedicated for filtering the air pulled into the facepiece by a blower unit to pressurize the eye region. Considering the potential encumbrances imparted to a user required to have two air-purifying filters mounted to a full facepiece APR (e.g., increased weight, reduced compatibility with optical devices, reduced visual field), particularly for users with tactical missions, an effort to fabricate and assess a single filter dual cavity concept was recently completed.

This investigation sought to quantify levels of protection afforded by a single filter dual cavity respirator concept under simulated workplace conditions; that is, while participants performed physical activities representative of tasks common to tactical law enforcement officers or military personnel. Several studies have measured simulated workplace protection factors (SWPF) to characterize respirator performance anticipated for usage in actual work environments (Hauge et al., 2012; Duling et al., 2007; Lawrence et al., 2006; Coffey et al., 2006; Zhuang et al., 2005; van der Gijp and Steenweg, 2004; Scanlan et al., 2003). However, as recognized by van der Gijp and Steenweg (2004), the simulation of a military work environment is difficult to achieve due to the varying nature of warfighter tasks and the settings in which missions take place. Therefore, a laboratory-based SWPF assessment was chosen for the present investigation over testing in a tactical field setting because it permitted a determination of the optimum performance of the dual cavity concept by reducing the impact of sources of variability through maintenance of tightly controlled study conditions.

METHODS

Test Participants

Twelve volunteers (8 males and 4 females) between the ages of 24 and 41 years (31 ± 5 yr; mean $\pm$ SD) participated in this study. Subjects weighed 79.1 ± 12.6 kg and were 175.3 ± 11.1 cm tall. All volunteers were civilians employed at the U.S. Army Edgewood Chemical Biological Center (ECBC). Signed informed consent was obtained for all subjects upon completion of volunteer agreement paperwork. Each volunteer also completed the Occupational Health and Safety Administration Regulation 29 CFR 1910.134 Respirator Medical Evaluation Questionnaire and was cleared for respirator wear and testing by medical personnel from the Kirk U.S. Army Health Center, APG, MD. After providing informed consent, volunteers completed the trait subscale of the State-Trait Anxiety Inventory (STAI; Spielberger, 1983). The trait anxiety inventory is a 20-item scale that evaluates how respondents generally feel and was used as a measure of anxiety tendency for each volunteer. Once completed, anthropometric measurements of the head and face were obtained. Subjects then received instructions regarding performance of the physical tasks comprising the mask wear trials of the investigation and were

required to perform each task for as long as they deemed necessary to be comfortable with task procedures.

Experimental Conditions

Respirator wear conditions included the Avon C50 (APR; Avon Protection Systems, Cadillac, MI) and the single filter dual cavity respirator concept (DC). Presentation of conditions was randomly assigned for each subject and volunteers were exposed to only one test condition on any given day. The C50 is a commercially available National Institute for Occupational Safety and Health (NIOSH) approved APR for chemical, biological, radiological and nuclear (CBRN) hazards. The C50 consists of a full-facepiece respirator and an inner nose cup that encompasses the mask's breathing zone, a single visor, and a single filter element cheek-mounted on one side of the facepiece.

The DC concept utilized the C50 facepiece configured with a customized internal fan, nose cup, and one-way valves. The air flow pathway of the DC concept is presented in Figure 1. The customized fan included a manifold fitted between a C50 filter housing and the customized nose cup that isolated the nose cup and eye cavity regions within the facepiece. The internal fan was powered to provide breath-assisted air to the nose cup during inhalation and to pressurize the eye cavity during both inhalation and exhalation (Figure 1). The direction of incoming air (nose cup or eye cavity) was controlled by two internal check valves that responded to the wearer's breathing cycle. The fan consisted of a stereolithography (SLA) impellor and a Faulhaber 1717T-006 SR motor (MICROMO, Clearwater, FL) in a customized SLA housing. The motor was operated at a voltage of 6.0 V and powered with a lithium-ion battery (ND2057, Inspired Energy, Inc., Newberry, FL). The nominal flow rate of the fan was $34 \text{ L}\cdot\text{min}^{-1}$. Both the APR and DC concept used a single filter element (CSCF50; Avon Protection Systems) mounted to the respirator facepiece during testing.

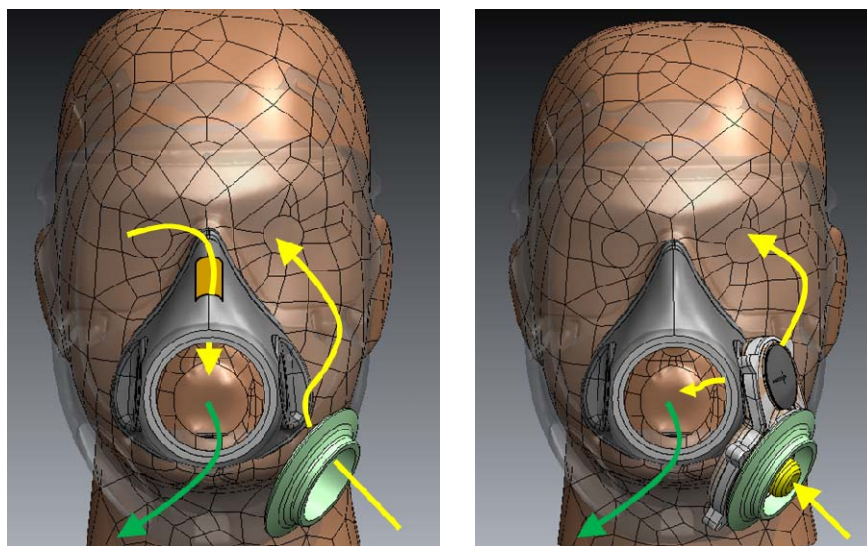


Figure 1. Schematic of flow paths of inhaled and exhaled air for the APR (left panel) and DC concepts (right panel).

Test Procedures

The planned series of experiments aimed to quantify protective performance in terms of quantitative protection factors over a range of physical tasks that simulated common tactical law enforcement or military personnel activities. Volunteers were given a properly sized Army Combat Uniform (ACU) to wear for each test trial. The ACU included a long-sleeve shirt, trousers, and a moisture-wicking t-shirt. In lieu of combat boots, volunteers wore their personal athletic shoes for testing.

Volunteer subjects were advised to get adequate rest, to eat breakfast and/or lunch, and to drink plenty of fluids, excluding alcohol and caffeine, before reporting to the laboratory. Male volunteers were also instructed to shave prior to each test session. Upon arrival, subjects dressed in an ACU and were prepped for heart rate monitoring by donning a chest-band transmitter and wristwatch receiver (Polar® S810i, Polar Electro, Inc., Lake Success, NY). Prior to commencement of a test session, volunteers completed the state anxiety subscale of the STAI to get a measure of state anxiety (STANX), which was an indicator of an individual's current level of anxiety (Spielberger, 1983).

Once the STANX was completed, the volunteer was prepped for testing. In-mask particle counts over the course of the mask wear trials were measured within each mask's nose cup using a PortaCount® Plus Respirator Fit Tester Model 8020 (TSI, Inc., Shoreview, MN) mounted to a tactical load bearing vest (BLACKHAWK!® S.T.R.I.K.E.® Tactical Armor Carrier, BLACKHAWK! Products Group, Norfolk, VA) and carried on the back of the test participant (Figure 2). The PortaCount was positioned to minimize potential flooding of the optics chamber with alcohol and tightly secured to the vest to minimize movement. This configuration permitted volunteers to move freely while performing the various physical activities with minimal interference from power cords, bench-top data acquisition systems and remote tethered sampling devices. Subjects donned a properly sized and fitted load bearing vest with assistance from test administrators. Then the test respirator was donned. A data cable from a vest-mounted data logger (XM8 Serial Data Logger, CAS Data Loggers, Chesterland, OH) was connected to the data port of the PortaCount for continuous recording of in-mask particle counts. A second data logger (Simple Logger II Model L432, AEMC Instruments, Dover, NH) was used to record pressure within the eye cavity of the DC concept respirator. The weight of a fully instrumented load-bearing vest was 5.9 kg.

With the test respirator and load-bearing vest in-place, the volunteer completed a pre-SWPF respirator fit test routine comprised of the five activities of normal breathing, deep breathing, rotating the head from side-to-side, nodding the head up and down, and rotating the jaw with the mouth held slightly open. Fit testing was accomplished using a separate table mounted PortaCount operated by a computer using FitPlus™ Fit Test software (TSI, Inc.). Each of the five activities was one minute in duration. An overall fit factor score based upon the five activities was derived, displayed and stored by the software at the end of the complete routine. In-mask particles were collected from the test respirator's nose cup via a PortaCount sample line attached to the external drink tube of the respirator. Particle concentration of the ambient air used for the pre-SWPF fit test was augmented with both a salt-generator (Model 8026 Particle Generator, TSI, Inc.) and with oil-burning lamps (Lamplight Original, Lamplight Farms, Inc., Menomonee Falls, WI) to ensure a challenge concentration above 50,000 particles per cubic centimeter (particles·cm⁻³) based upon recommendations set-forth by Harrison and Liang (2005). The pass/fail criterion for an acceptable fit was a minimum fit factor (FF) level of 2000 to reflect the NIOSH requirement for CBRN APR certification (NIOSH, 2003).

After completing the pre-SWPF fit test, the PortaCount sample line from the unit mounted to the load-bearing vest was connected to the test respirator's external drink tube, all data acquisition connections were secured, and operation of the heart watch was confirmed. A pre-SWPF heart rate was recorded and initial subjective ratings of respirator comfort, thermal sensation of the face, and perceived exertion were then obtained. The Breathing Apparatus Comfort Scale (BACS) measured subjective comfort on an eleven-point Likert scale with descriptors ranging from zero (very, very uncomfortable) to

10 (very, very comfortable) (Abadie and Carroll, 1993). Test participants rated sensations of warmth or coldness associated with the respirator using the American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) Thermal Sensation Scale (ASHRAE, 1993). The ASHRAE scale measured thermal sensation on a seven-point Likert scale with descriptors ranging from positive 3 (hot) to negative 3 (cold).



Figure 2. Load-bearing vest instrumented with data acquisition components.

The battery of operationally relevant physical activities comprising the SWPF investigation was then initiated. The set of tasks represented light to heavy intensity physical workloads (Table I). Brief descriptions of each activity in the order in which they were completed are as follows:

Treadmill (Trackmaster TM500, JAS Manufacturing, Carrollton, TX) walking (Walk) involved walking on a level grade at a pace of $1.6 \text{ m}\cdot\text{s}^{-1}$ for three minutes. As for the pre-SWPF testing, the fit test (Fit test) routine included the five activities of normal breathing, deep breathing, moving the head from side-to-side, nodding the head up and down, and rotating the jaw. The Fit test was performed while standing on the treadmill deck with the treadmill turned off; each of the five activities was one minute in

duration. A treadmill run at $2.2 \text{ m}\cdot\text{s}^{-1}$ was initiated once the Fit test was completed. The running task (Run) was two minutes in duration.

The low crawl (Crawl) required volunteers to be in a prone position on their stomach with the head turned to one side and as close to the ground as possible. The Crawl was performed repetitively until the allotted two minute task time had transpired. The low crawl was done on 9.5 mm thick rubber mat. Volunteers carried a simulated rifle while performing the Crawl task.

Table I. Physical Activities of the SWPF Test

Task Order	Activity	Duration (min)	Relative Workload
1	Walking	3	Low to moderate
2	Standing rest	1	Low
3	Fit test	5	Low
4	Running	2	Moderate to high
5	Standing rest	1	Low
6	Low crawl	2	Moderate to high
7	Standing rest	1	Low
8	Load lift and carry	2	Moderate
9	Standing rest	1	Low
10	Stair climb	2	High
11	Standing rest	1	Low
12	Shoveling	2	Moderate to high
13	Standing rest	1	Low
14	Simulated rifle firing	3	Low to moderate

The load lift and carry exercise (Lift) involved lifting and carrying two 18.9 L buckets, one in each hand, over a fixed distance repetitively. Each bucket was filled with sand and capped with a lid to provide a weight of 6.8 kg for a total load weight of 13.6 kg. After lifting the buckets, the subject carried them in a straight line for 3.8 m, stopped and then slowly lowered them to the floor by bending at the knees. Once placed on the ground, subjects paused for approximately five seconds before repeating the lift and carry activity. These motions were performed repetitively until the allotted two minute task time transpired.

Two minutes of stair climbing (Stairs) were performed on a StairMaster 7000 PT Stepmill (Stairmaster Health and Fitness Products, Kirkland, WA). This activity required volunteers to step at a rate of $60 \text{ steps}\cdot\text{min}^{-1}$ for two minutes. The shoveling activity (Shovel) involved self-paced shoveling of sand from one container to another. Two 89 cm long, 63 cm wide, and 30 cm deep containers were positioned side-by-side and one was filled with sand. Using a 122 cm handled round point shovel, subjects dug into the sand-filled container, scooped up a shovel-full of sand, and moved it into the opposite container repetitively for two minutes. If the volunteer managed to empty the full container before the allotted activity time transpired, they were instructed to proceed with the task by shoveling the sand back into the original bin.

A Tactical Weapon Simulator - Classroom Trainer (Laser Shot, Stafford, TX) was used for the rifle firing activity (Rifle). Subjects used a non-tethered simulated M4 rifle that used an eye-safe laser to replicate firing of ammunition for this task. Volunteers stood 4.5 m from video screens used for the task.

With the simulated M4 held in both hands in a ready position, the simulated firing scenario was started and targets were projected onto the video screens. When the initial target appeared, the subject raised the weapon to the firing position, aimed the weapon, and fired at the target until a hit occurred or the target left the screen. The Rifle activity was programmed to run for three minutes; however, the measured duration of the activity ranged between 2.2 min and 4.6 min depending upon user performance.

Heart rate was recorded at the beginning and end of each physical activity. Subjective ratings of respirator comfort and thermal sensation of the face were obtained at the end of each exercise. Environmental conditions of temperature and humidity were also recorded at this time. Data collection of in-mask and ambient particle concentrations was stopped once the Rifle activity was completed. Once final responses for comfort and thermal sensation were obtained, subjects doffed the test respirator, a test administrator removed the load-bearing vest with measuring components, and the subject completed a post-test STANX. The time to complete all of the test procedures for a single respirator condition, including preparation and post-test processing averaged 47 ± 5 min of respirator wear independent of condition. Of this, the entire SWPF activity period averaged 31 ± 3 min.

Measurements of In-mask and Ambient Particles

All PortaCount devices used in this investigation were calibrated prior to use. Each unit also underwent a daily self-check according to manufacturer's directions. With one PortaCount dedicated to continuous in-mask sampling, additional particle counters were positioned at each individual exercise station in the test facility for monitoring and recording of ambient particle concentrations. As such, only one particle counter was used for monitoring ambient concentrations at each exercise station. Each PortaCount was set to count mode for continuous measurement of particle concentrations. Ambient particle counters were positioned as close to the test participant as practical so that ambient samples could be obtained reasonably close to the face of the respirator wearer. Ambient particle counters were connected to a computer RS232 serial interface and data were collected and stored every two seconds using HyperTerminal software.

In-mask particles were obtained from the nose cup of each respirator test bed system through the drink tube. In-mask particle concentrations were also measured within the eye cavity of each system using a separate PortaCount connected to a sample probe mounted on the right side of the respirator's facepiece just below the visor during the Walk, Fit test, Run, and Stairs activities. Eye cavity particle concentrations were recorded with a separate data logger (XM8 Serial Data Logger, CAS Data Loggers). The eye cavity PortaCount and data logger were positioned next to the treadmill and StairMaster during testing and were not mounted on the tactical vest.

Data collection of all in-mask and room ambient particle samples was time-synchronized to assure matching of data samples during post-test data analysis. This required test administrators to simultaneously switch both the in-mask and room PortaCount devices from average count mode to continuous count mode at the start of an activity and then switch back at the end. As for the pre-SWPF fit test, particle concentration of the ambient air was augmented with salt-generators and/or oil-burning lamps to ensure a minimum $50,000 \text{ particles} \cdot \text{cm}^{-3}$ challenge concentration. Ambient particle sizes, measured on three separate occasions with an electrostatic classifier (Model 3080L, TSI, Inc.), ranged from approximately $0.03 \mu\text{m}$ to $0.26 \mu\text{m}$ count median diameter throughout this investigation.

A pressure sensor (model HSCMRRN001NDAA3, Honeywell International Inc., Golden Valley, MN) with a differential pressure range of $\pm 2.54 \text{ cm H}_2\text{O}$ was used to monitor pressures within the eye region of the DC concept. The pressure sensor was mounted inside the DC facepiece; output wires were exteriorized through a sealed port on the filter mount blank positioned in the unused facepiece filter mount. As stated previously, eye cavity pressures were recorded continuously with a data logger.

Pressure data were also time-synchronized to assure matching of data samples with SWPF activities during post-test data analysis.

Data Analysis

Instantaneous respirator SWPFs were calculated post hoc from recorded, synchronized in-mask and ambient particle counts according to the equation:

$$SWPF = \frac{C_A}{C_R} \quad (1)$$

where: SWPF = simulated workplace protection factor

C_A = particle concentration in the ambient sample

C_R = particle concentration in the respirator sample.

If no in-mask particles were counted (recorded as a zero), a value of 0.3 was used as the respirator sample to avoid dividing the ambient concentration by zero when calculating a SWPF. Overall SWPF for each SWPF activity was derived from the equation:

$$Overall \ SWPF = \frac{n}{\frac{1}{SWPF_1} + \frac{1}{SWPF_2} + \frac{1}{SWPF_{n-1}} + \frac{1}{SWPF_n}} \quad (2)$$

where: SWPF = simulated workplace protection factor from each recording of in-mask and ambient counts

n = number of instantaneous SWPF derived within each SWPF activity.

All FF and SWPF data were log transformed ($\log_{10}$) for analysis. Pre-SWPF fit test results were compared between APR and DC conditions using independent sample T-tests. Analysis of variance was used to test for statistical significance of SWPF performance and subjective data within and between experimental conditions. Appropriate post hoc analyses were applied to identify between condition differences if warranted. Statistical computations were performed using Predictive Analytics Software, version 17.0 (SPSS, Inc., Chicago, IL). All FF and SWPF data are presented as log transformed mean $\pm$ standard deviation (SD) unless otherwise noted. Statistical significance was accepted at the $p < 0.05$ level.

RESULTS

Pre-SWPF Fit Test Results

A total of 23 SWPF trials were completed; one APR trial could not be administered due to availability of a volunteer. All subjects achieved a FF above 2000 ($\log_{10}FF \geq 3.30$) for each respirator condition. Pre-SWPF trial $\log_{10}FF$ averaged 4.60 ± 0.48 for the APR and 4.99 ± 0.61 for the DC condition. The difference between conditions was not significant.

Simulated Workplace Protection Factors

Independent of SWPF activity, room temperatures averaged $23.0 \pm 0.2^\circ\text{C}$ and $23.0 \pm 0.1^\circ\text{C}$ for the APR and DC conditions, respectively. Ambient aerosol concentrations ranged from 10500 to 135000 particles $\cdot\text{cm}^{-3}$ across all SWPF tasks independent of respirator condition. Average concentration for the Rifle task (60212 ± 24390 particles $\cdot\text{cm}^{-3}$) was significantly lower than both the Walk (86659 ± 20259 particles $\cdot\text{cm}^{-3}$) and Fit test (90009 ± 19476 particles $\cdot\text{cm}^{-3}$) tasks, but no other differences among SWPF tasks were found independent of condition. Ambient concentrations were significantly higher for the DC condition during the Walk (93617 ± 21178 particles $\cdot\text{cm}^{-3}$) compared to the APR for the same activity (79771 ± 16681 particles $\cdot\text{cm}^{-3}$); however differences between respirator conditions were not significant for the remaining SWPF tasks.

The example of continuous in-mask particle counts and SWPF over the course of a SWPF trial presented in Figure 3 demonstrates the variability of respirator fit over time throughout wear trials. Average task-by-task Overall SWPF results for both the nose cup ($\text{Log}_{10}\text{SWPF}_{\text{Nose}}$) and eye ($\text{Log}_{10}\text{SWPF}_{\text{Eye}}$) regions for the APR and DC conditions are presented in Figure 4. Overall SWPF_{Eye} values did not differ between the APR and DC conditions for any of the SWPF tasks that included measurements of particles within the eye region (Figure 4). In contrast, Overall $\text{SWPF}_{\text{Nose}}$ were significantly higher for the DC condition compared to the APR condition during the Fit test, Lift, and Rifle activities; no other differences between conditions were found for the remaining activities.

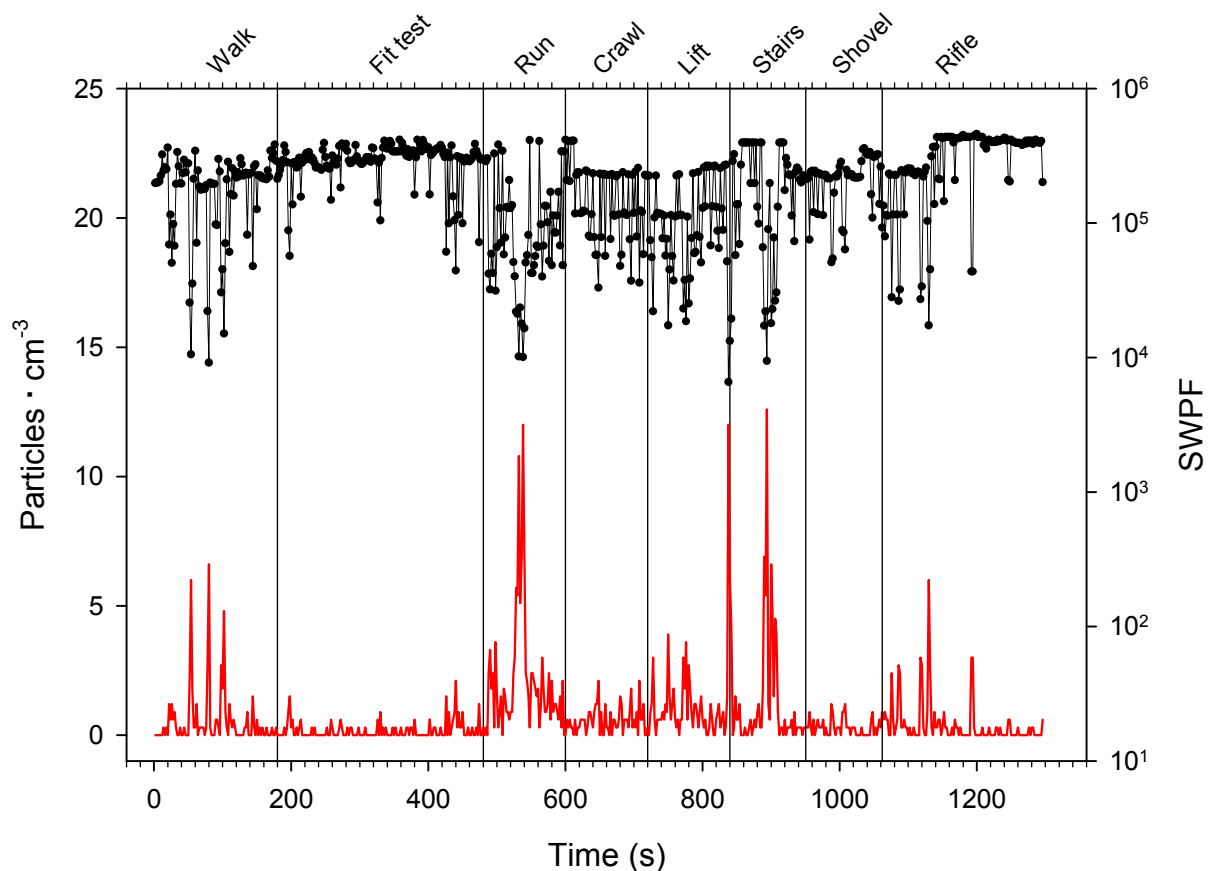


Figure 3. In-mask particle counts (solid line) and $\text{SWPF}_{\text{Nose}}$ (line with dot symbols) over the course of an individual SWPF trial with the APR.

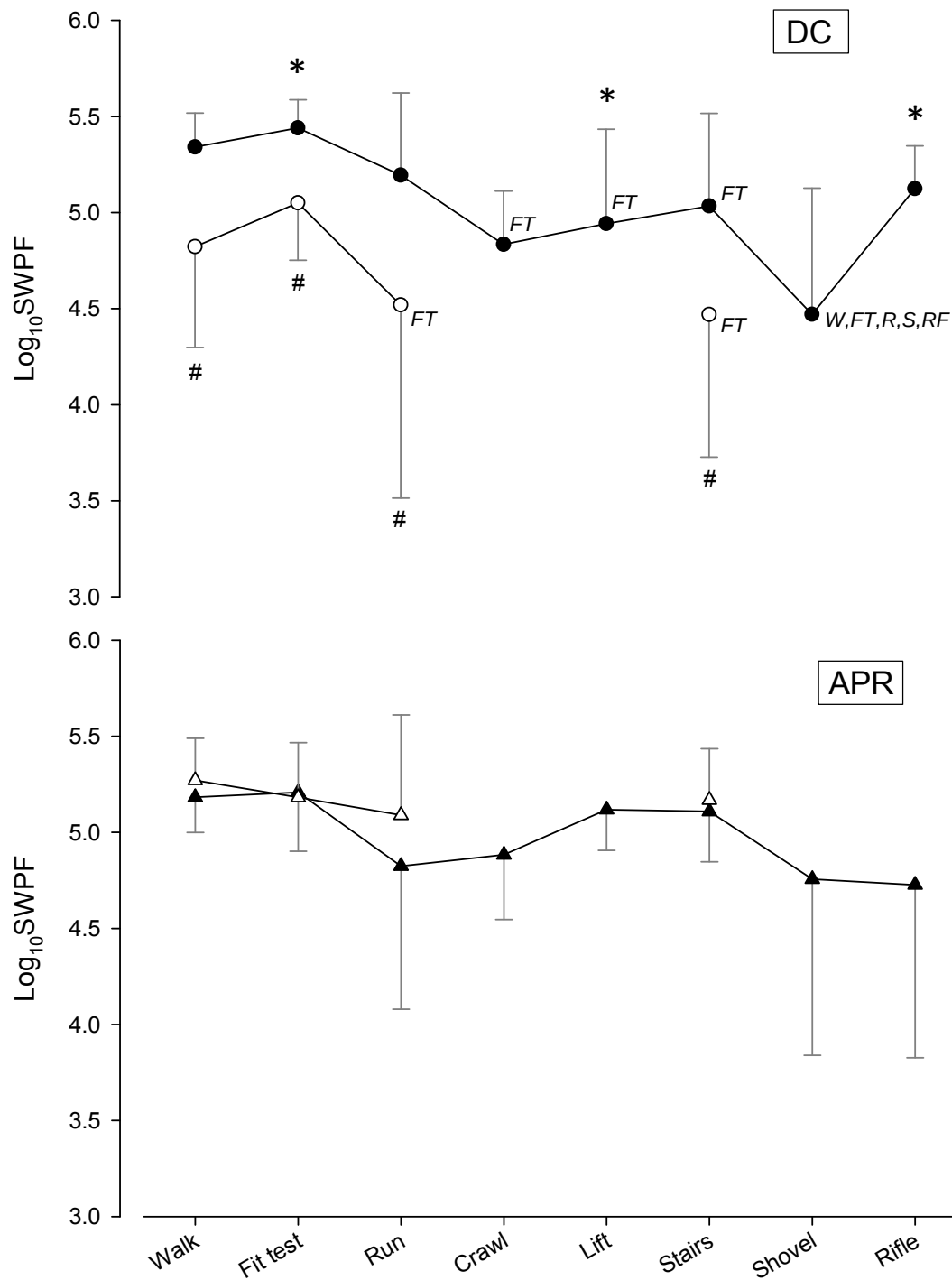


Figure 4. Average ($\pm$ SD) SWPF_{Nose} (closed symbols) and SWPF_{Eye} (open symbols) by activity for the DC concept (top panel) and APR (bottom panel). * = significantly different vs. APR; # = significant different vs. SWPF_{Nose}; letters designate significant differences from tasks within conditions (W = Walk, FT = Fit test, R = Run, S = Stairs, and RF = Rife).

No effects of activity on $SWPF_{Nose}$ or $SWPF_{Eye}$ results were evident for the APR condition. Likewise, no differences between average $Log_{10}SWPF_{Nose}$ and $Log_{10}SWPF_{Eye}$ values were found when collected simultaneously during the Walk, Fit test, Run, and Stairs tasks. Average $Log_{10}SWPF_{Eye}$ results differed significantly from Fit test values for the Run and Stairs activities for DC trials. Average $Log_{10}SWPF_{Nose}$ results obtained during the Crawl, Lift and Stairs tasks also differed significantly from Fit test results. The Shovel task resulted in the lowest average $Log_{10}SWPF_{Nose}$ value during wear of the DC concept, which differed significantly from the Walk, Fit test, Run, Stairs, and Rifle results. Differences between average $Log_{10}SWPF_{Nose}$ and $Log_{10}SWPF_{Eye}$ values were found for four tasks that included measurements of eye region particles.

Average pressures recorded from the eye cavity region of the DC concept respirator by SWPF activity are presented in Figure 5. These averages represent only those data that did not exceed the limited range of the DC concept's imbedded pressure transducer. Eye region pressures varied considerably among SWPF activities; however, the constraints of the range of measureable pressures of the sensor prevented statistical comparisons among the different tasks. Therefore, in-mask pressure data were assessed to simply define the occurrences of positive or negative pressures within the DC respirator eye cavity for each SWPF task. The occurrence of negative pressures recorded during wear of the DC respirator concept is presented in Figure 5. Relatively few instances of negative pressure within the eye region of the DC concept were found during the Walk, Fit test, Run, and Rifle activities. Approximately one-fifth to one-quarter of the eye cavity pressure data was negative for the remaining SWPF activities.

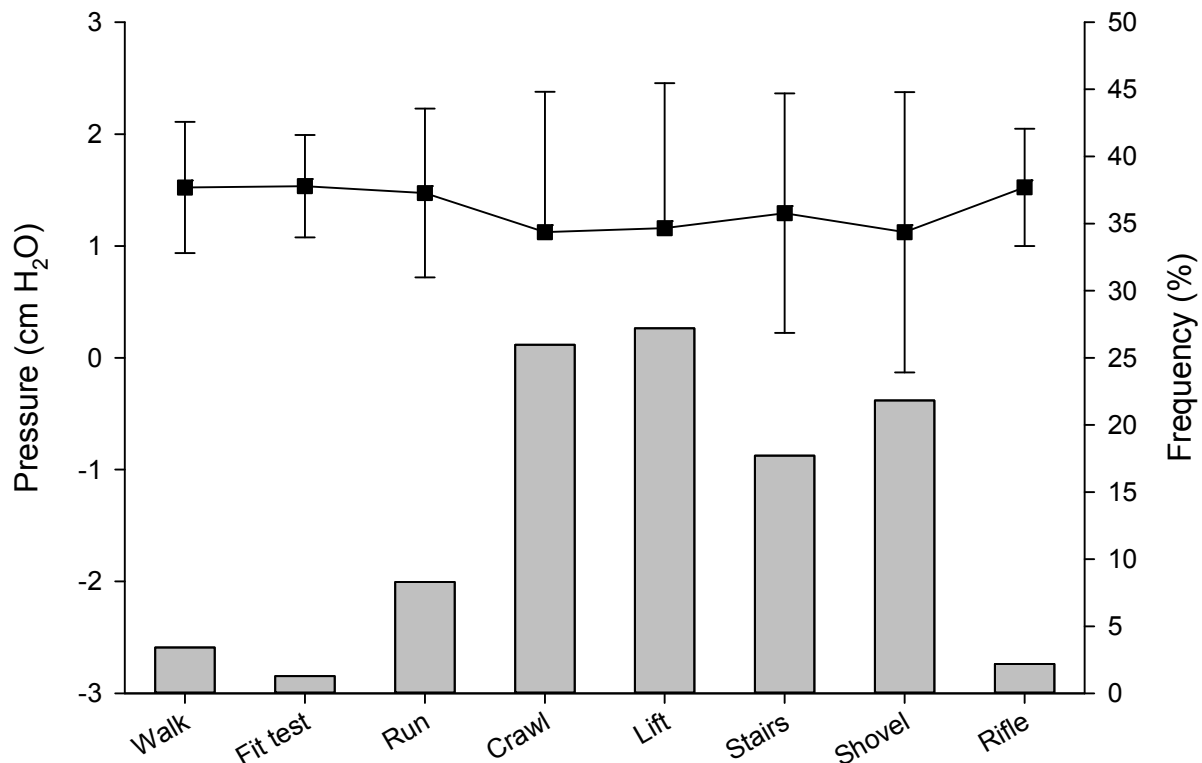


Figure 5. In-mask pressures (■) from the eye cavity of the DC concept by SWPF activity. Data represent average ($\pm$ SD) for measurements that did not exceed the pressure range of the embedded pressure sensor. Bars represent the frequency of negative pressures for each activity regardless of their magnitude.

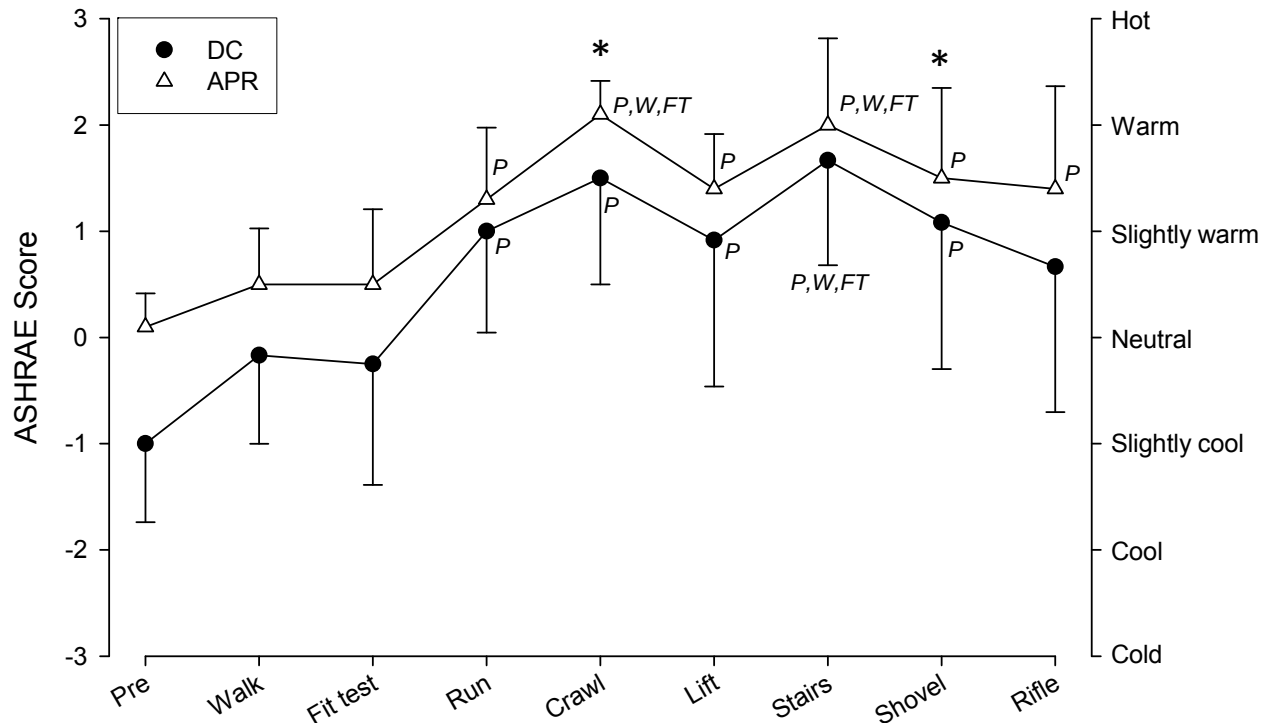


Figure 6. Average thermal sensation responses by SWPF task. * = significantly different vs. APR; letters designate significant differences from tasks within conditions (P = Pre, W = Walk, and FT = Fit test).

Subjective Responses

No differences in anxiety scores between APR and DC respirator test conditions were found before or after the SWPF routine. Differences between pre and post-test STANX scores within conditions were not significant. Similarly, there were no significant respirator comfort differences within or between the DC and APR conditions at anytime. Average thermal sensation responses by SWPF task are presented in Figure 6. The warmest thermal sensation ratings were observed for the APR condition and the coolest ratings were found with the DC concept. Differences between conditions were significant during the Crawl and Shovel activities. Within the APR condition, thermal sensation ratings for the Run task and each of the following activities differed significantly from the pre-SWPF average score. Additionally, thermal ratings for the Crawl and Stairs tasks differed significantly from both the Walk and Fit test ratings. Thermal sensation ratings among tasks within the DC condition demonstrated significantly more warmth sensation on average for the Run task and each of the subsequent activities other than the Rifle compared to the pre-SWPF score. Thermal sensation ratings also differed significantly between Stairs and Walk tasks and Stairs and Fit test tasks during DC conditions.

DISCUSSION

This investigation quantified levels of respiratory protection and user comfort of a single filter, dual cavity respirator test bed compared to a commercial off-the-shelf APR under wear conditions representative of tactical law enforcement and military operations. The single filter dual cavity test bed was configured to provide breath-assisted air to the breathing zone (i.e., nose cup) during inhalation and to pressurize the eye cavity during both inhalation and exhalation. In theory, this configuration would create a constant amount of positive pressure within the space that is encapsulated by the peripheral seal of the facepiece with a wearer's face. In turn, this overpressure would counteract any potential inward leakage of contaminants due to very short and infrequent breaks of the peripheral seal.

In-mask pressure data showed that the DC concept did not always maintain positive pressure within the eye cavity across the various SWPF activities. Negative pressures occurred most frequently during performance of the moderate to hard physical tasks when inhalation demands of the users likely exceeded the air flow rate of the internal fan. Others have reported similar occurrences of overbreathing fan-supplied air of positive pressure respirators (Koh et al., 2011; Mackey et al., 2005). Limited data on ventilation rates obtained from two test participants separate from the experimental test trials found that inhaled minute volumes exceeded the internal fan's $34 \text{ L}\cdot\text{min}^{-1}$ flow rate during the Run, Crawl, Lift, Stairs, and Shovel activities. However, despite the high frequency of negative pressures within the eye cavity of the DC concept during these activities, average DC SWPF_{Eye} measurements during the Run and Stairs tasks did not differ from those found for the APR. These results indicate that the positive pressure within the eye cavity of the DC concept was inadequate for preventing contaminant infiltration during momentary breaches of the seal. Whether or not the number of particles that entered the eye cavity was correlated to the amount of negative pressure created within this region could not be determined during this investigation due to the acknowledged limitations of the pressure sensor built into the DC concept. Anecdotally, average SWPF_{Eye} measurements during the Run and Stairs activities were significantly lower compared to Fit test SWPF_{Eye} measurements, when the frequency of in-mask negative pressures was lowest.

Pelfry et al. (2010) demonstrated a dual cavity respirator concept that maintained positive pressure in the eye cavity during head movement exercises common to standard respirator fit test routines. Even when the peripheral mask seal was deliberately breached, causing the eye cavity of the facepiece to lose positive pressure, in-ward leakage of particulates into the nose cup of their DC respirator was minimal. Although no results of particle infiltration into the eye region of the dual cavity respirator were available during this seal-breathing maneuver, the number of particulates was likely higher relative to the nose cup measurements. As such, the customized nose cup used by Pelfry et al. (2010) appeared to function to minimize inward leakage of particulates from the eye region into the breathing zone of their dual cavity system for this single maneuver. When measured, average SWPF_{Eye} results were significantly lower compared to $\text{SWPF}_{\text{Nose}}$ values for the DC concept tested in the present investigation, indicating that the nose cup design used for the DC also had a good seal to the face, not only during head movements of a standard fit test, but also across a range of physical activities. Differences between SWPF_{Eye} and $\text{SWPF}_{\text{Nose}}$ for the APR condition were not anticipated, nor observed, based upon the inhaled airflow pathway resulting from the system's design, which essentially channels air from the eye cavity into the breathing zone during inhalation.

Both the APR and DC concept provided high levels of respiratory protection for all of the SWPF activities. The SWPF_{Eye} levels were lower for the DC concept compared to the APR, but did not differ significantly; $\text{SWPF}_{\text{Nose}}$ values calculated for the DC concept were similar to those of the APR for like activities with the exception of the Fit test, Lift, and Rifle tasks. However, as stated by Roberge et al. (2008), there may not be a practical difference between $\text{SWPF}_{\text{Nose}}$ measurements exceeding 100,000 because the accuracy of the PortaCount for measurements of protection factors in excess of 10,000 have not been well described. As such, the results of this investigation do not clearly demonstrate a

substantial advantage in respiratory protection of the single filter dual cavity concept over a properly sized and fitted APR. These findings indicate that additional refinements to the DC concept are needed before definitive improvements in protection over those of a standard full-facepiece APR are possible. Based on recent evidence from Koh et al. (2011), which suggests that even tight-fitting PAPRs with supplied airflow rates exceeding $114 \text{ L}\cdot\text{min}^{-1}$ do not exclude contaminant infiltration into the facepiece, it is questionable as to whether or not the next iteration of the DC concept needs to have a fan that supplies filtered air at a higher flow rate to the eye cavity. Another design factor of the DC concept that may have contributed to the comparable SWPF performance with the APR was that the facepiece periphery in the chin area of the C50 had to be trimmed just slightly to accommodate the customized DC nose cup. Although speculation at this point, it is possible that this may have led to direct leakage from outside the respirator near the chin into the facepiece.

Based on previous findings regarding the cooling potential of ambient air with a low-flow blower (Carette, 2013), wear trials with the DC concept provided an opportunity to further quantify subjective ratings of comfort and thermal sensation related to ambient air supply within an APR facepiece. Comparison of facial thermal sensation ratings showed that the DC concept produced cooler sensation ratings than the APR condition across all SWPF tasks; however, statistical differences between conditions were only found during the Crawl and Shovel activities. Despite these differences in thermal sensation, subjective ratings of comfort did not differ between DC and APR conditions at any time, suggesting that the ambient air supply to the face provided by the DC concept had little effect on wearer comfort during the SWPF trials under temperate ambient conditions. The findings of Johnson et al. (2005), which showed that cooling advantages of a PAPR were negated when air flow was limited below approximately $72 \text{ L}\cdot\text{min}^{-1}$ during heavy exercise, suggest that the facial air flow supplied by the DC concept was design limited in its ability to substantially improve subjective feelings of thermal sensation and user comfort.

An outcome of this investigation that should not be overlooked was the demonstrated ability to quantify instantaneous respirator fit of freely moving subjects during simulated operational activities. The methods devised to continuously measure and record in-mask particulates in conjunction with ambient aerosol challenge concentrations proved to adequately quantify respiratory protection levels while volunteers performed physical activities more closely related to tactical law enforcement and military activities. Similar respirator fit testing methods were recently implemented by Hauge et al. (2012) during simulated health care tasks. The SWPF activities selected in the present investigation offered more in-depth information regarding performance and design of the different test bed respirators than would be achieved solely from standard fit test head movements. Additional research is needed to determine if the designed SWPF approach may be able to bridge the gap between laboratory and true field performance of respirators. However, the established test methods provide a simple means for future comparisons.

CONCLUSIONS

The findings presented herein demonstrate that the single filter dual cavity test bed respirator did not completely prevent particulates from entering the facepiece during wear trials that simulated tactical operational activities. Even so, the DC concept provided high levels of respiratory protection that either exceeded or equaled levels afforded by a properly sized and fitted APR during the performance of like tasks. Although advantages provided by the DC concept towards improved subjective feeling of thermal sensation compared to an APR were evident, they did not manifest into better ratings of respirator comfort. On the basis of these findings, additional refinements to the single filter dual cavity pressurization concept need to be explored before definitive improvements in protection and user comfort over those of a standard full-facepiece APR are likely to be found.

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