

Evaluating Simulated Workplace Protection Factors for a First Responder Low-Level Protective Ensemble

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ABSTRACT

First responders are required to wear multiple layers of personal protective equipment while performing a range of physiologically demanding tasks for long periods of time. They are often required to wear high levels of respiratory protection, which can adversely impact their ability to work safely. The goal of this study was to evaluate the respiratory protective performance of a nominally lower level protective system in the course of performing typical first responder activities, which included an N95 filtering facepiece respirator in combination with a disposable hooded suit and latex gloves.

Methods: Eleven subjects (10 male; 1 female) were recruited for a range of facial sizes. Each subject donned an N95 filtering facepiece respirator following the Canadian fit test protocol. The subject then donned the hood, entered a test chamber and performed a 31-min exercise protocol. Using two Portacount instruments, one-second real-time measurements of particulate concentration were simultaneously performed inside and outside the respirator facepiece. Subjects exited the chamber, removed the hood and completed a final quantitative fit test.

Results: While limited by the small number of subjects and few small faces, we were able to show that N95 filtering facepiece respirators can provide a high degree of protection (simulated workplace protection factors ranging from 100-1000). We found no consistent relationship between initial and final fit factors. Final fit factors and SWPF were strongly correlated.

Conclusion: The two-instrument method combined with a challenging exercise protocol can elucidate several important respirator performance factors, including most challenging work tasks, effects of sweating and higher metabolic output, and interactions from other personal protective equipment.

Keywords: Simulated workplace protection factors, First responders, Ensemble, Personal protective equipment (PPE).

INTRODUCTION

As a premise of employment, first responders often put themselves in potentially dangerous situations to protect the lives of others. When responding to a chemical, biological, radiological and nuclear (CBRN) event, it is important that a first responder can rely on their respirator to provide an adequate level of protection. A quantitative test that employs a short limited set of exercises may not provide sufficient information about respirator fit for such hazardous work.

Each class of respirator has an assigned protection factor (APF), which is the protection a trained population can expect to receive from a properly fitting and functioning respirator. APFs are used by regulators and standards development organizations, such as the US Occupational Safety and Health Administration (OSHA) and the Canadian Standards Association (CSA) - Z94.4 (OSHA 1998a; CSA 2011a). The APF is multiplied by a safety factor, to determine the necessary fit factor each employee is required to receive prior to being issued their respirator; this takes into account expected degradation between the fit factor and the performance expected in the workplace (which should not be worse than the APF). As a result, APFs are conservative values and may underestimate achievable performance.

An assigned protection factor should be derived from measures of actual respirator performance conducted on multiple workers performing a range of work tasks in a variety of workplaces. Measuring respirator performance in the workplace - a workplace protection factor (WPF) - requires full-shift samples of inside and outside concentrations of a contaminant during work activities. High quality WPF data could provide adequate knowledge of how an individual's respirator performs in a given industry and perhaps eliminate the need for a safety factor.

Previous workplace protection studies in industrial settings have compared 8-hr gravimetric samples collected inside the respirator and on the lapel (Myers et al. 1995; Zhuang and Myers 1996; Myers and Zhuang; Myers, Zhuang, and Nelson 1996). Subjects usually receive a qualitative fit test prior to WPF sampling and their activities are noted throughout the day. This test protocol cannot be easily performed with first responders because their exposures and activities are unpredictable.

Hence, it is only possible to measure the performance of a respirator in first responder settings using a simulated environment, in which subjects (ideally first responders) perform typical field tasks. A proposed methodology has been described for conducting a simulated fit or protection factor assessment using two Portacounts continuously monitoring inside facepiece and ambient concentrations (Gijp and Steenweg 2004; Hauge et al. 2012). By controlling the work-rate it may be possible to use simulated settings to provide very accurate information regarding the fit a respirator might provide to first responders. This knowledge could lead to more informed respirator selection.

The goals of this research paper are to describe a novel methodology for conducting simulated workplace protection factor assessments of a low level protective ensemble using real-time data collection, and to compare quantitative fit factors and SWPFs for a small group of first responders wearing N95 filtering facepiece respirators with a disposable hooded suit and nitrile gloves.

METHODS

Equipment

A test chamber was set up to have sufficient space for one volunteer to perform the activity routine, with one staff operator present to assist and carry the sampling instrument. The test chamber consisted of a 3.1 m (width) x 5.8 m (length) x 2.2 m (height) (volume=39.5m³) portable garage tent

retrofitted with plastic windows with an antechamber on one end. The antechamber allowed easy entry and exit from the chamber with minimal disturbance to a uniform aerosol concentration. Experiments were conducted on 4 separate days; across all days, as measured by the N95 Companion (Model 8095, TSI Incorporated, Shoreview MN) the concentration inside the tent ranged from 1500 to 5000 particles (p)/cm³. The N95-Companion is recommended when an N95 respirator is used. The tent was lined along the inside walls with plastic drop sheets and a large tarp draped along the floor and contained various equipment needed to perform the activity routine, including a treadmill, step ladder, weighted dummy, and a loaded cart.

Within the tent, eight salt aerosol generators (TSI Model 8026) and fans at either floor or waist height in each corner were used to maintain a steady uniform aerosol concentration throughout the space. The aerosol generators were operated as the operation manual specifies by dissolving a salt tablet in water, yielding a 2% NaCl solution (TSI Incorporated 2014). Concentrations in the tent ranged from 40,000 to 80,000 p/cm³. The N95 Companion uses an electrostatic classifier to select only particles which are negatively charged and small in size (40-60 nm) to be counted by a condensation particle counter (Portacount). The high concentrations in the tent would permit a reliable measurement of protection factor greater than 6,500 after particles pass through the classifier. Validation of the uniformity of the challenge aerosol was assessed by measuring the concentration at various locations and heights throughout the chamber; these varied by no more than 15%.

Two TSI Portacount Plus (Model 8020) with N95-Companion™ (TSI Model 8095) instruments were used to simultaneously measure concentrations inside and external to the respirator facepiece. The two instruments were previously calibrated together over a range of ambient concentrations to ensure their measurements would be within 15% of each other. A correction factor derived from the ratio of side-by-side ambient concentration measurements was used to correlate the two instruments' results after data collection was finished.

Tests were usually performed at ambient temperature. A portable air conditioner (Simplicity SPAC9507, 9500 BTU/h) was used to maintain humidity levels at less than 60% (CSA 2011b). Environmental conditions were monitored with a temperature/humidity probe (The Dickson Company Model TH300) inside the chamber.

Software developed by the Royal Military College of Canada (RMCC) was used to record second-by-second particle counts from each instrument connected to a computer laptop. The software collects information about activity timing and operator comments, and displays approximate instantaneous and cumulative protection factors in real-time. Side-by-side data collection from two instruments is conducted by simultaneously starting the software on each computer, with activity timing controlled with a timer inside the tent, correlating with the activity routine timing programmed into the computer.

A sampling tube was attached to a probe affixed to the side of the respirator facepiece. The instrument used to sample inside-facepiece concentrations was connected to a Bluetooth device and an external battery supply and placed in a case with the sampling tubes extending through a hole in the side of the case. This case was transported by a staff operator inside the chamber throughout the activity routine. Data from the instrument were recorded via the Bluetooth connection by a laptop located outside the chamber.

Also located outside the chamber were the second instrument and a second laptop computer, which were used to measure and record chamber concentrations via a sampling tube extending into the chamber through a hole in the tent wall.

Activity Routine Development

Through consultation with various first responder groups and in accordance with the recommendations of Z1610-11(CSA 2011b), an activity routine was developed to incorporate workplace activities commonly used by police emergency response, police public order, firefighters, paramedics and CBRN response teams responding to a CBRN event (Table I). Although some of the activities are more relevant to certain groups than others, the variety of activities in the routine ensured that the protective system could be evaluated for a wide range of first responder use. For example, the activity “perform traffic gestures” would be more relevant to police public order units while “squat, turn over manikin and examine” would be more relevant to paramedics. Activities that produce a wide range of basic body and head movements and may potentially place added stress on the seal of the respirator were also included in the protocol (e.g. “bend over” and “lunge leg and look”).

Table I. Exercise Routine Performed during SWPF

Activity #	Activity
1	Stand still, normal breathing
2	Bend over for 15 sec, rest for 15 sec, and repeat.
3	Smile, frown, yawn and rotate jaw; repeat 5 times, every 10 sec
4	Lunge right leg forward and turn head left and right, tilt head forward and backwards, stand, repeat with alternate leg. Repeat alternating legs 4 more times (once every 12 sec)
5	Step onto step stool or platform, raise left arm to touch ceiling, small jump off platform, touch floor with left arm, repeat and raise alternate arm (5 times, once every 10 sec)
6	Jog on treadmill (or equivalent) at 7 km/h (4.3 miles per hour) and zero inclination
7	Jog on treadmill (or equivalent) at 4 km/h (2.5 m/h) and zero inclination
8	Stand still, normal breathing
9	Lie in prone position, look at target objects (10 sec), rest (5 sec), repeat 3 times, stand
10	Carry equipment (5 sec), load and pull the cart (15 sec), unload equipment (10 sec), repeat once
11	Perform traffic control gestures
12	Crawl on hands and knees (5 sec), look up, left and right (5 sec), repeat 5 times
13	Climb up and down 2 rungs of the ladder, repeatedly (once every 6 sec)
14	Squat, turn over manikin and examine, repeat once
15	Drag manikin by a rope tied under the arms (15 sec), rest (5 sec), repeat 2 times
Repeat exercises 1-15	
Final	Stand still, normal breathing

The 31-min activity routine consisted of two repetitions of 15 1-min activities followed by a final 1-min normal breathing activity (Table I). Each activity was repeated to reveal whether particular activities had a consistent impact on respirator performance as well as to evaluate the effects of increasing work rate and sweating over the course of the routine.

The activity metabolic work rate was calculated using table A.1 (Classification of metabolic rate and examples of corresponding activities) in the International Organization for Standardization (ISO) standard (ISO 2007). The work rates ranged from light to heavy work rates and generated an overall moderate metabolic work rate for the complete routine (ISO 2007). Running on the treadmill was incorporated in order to bring test participants to a high work rate. Rest periods and light work rate activities were interspersed between the high work rate activities to maintain the test subject's stamina and allow time to recuperate. Rest periods (i.e. so-called normal breathing) also provided a 'baseline' measure with no movement to assess the long term effects of dislodging the respirator facepiece. The total duration and nature of the activities were generally sufficient for test participants to achieve sweating and maintain a moderate work rate.

Experimental Protocol

Initial Quantitative Fit Test

Eleven subjects were recruited (10 males and 1 female) to participate in the study. Initial subjects were first responders but the subject pool was subsequently supplemented with non-responders to obtain a broader anthropometric distribution. The final group included 6 responders and 5 non-responders. Two facial distribution panels, the Bivariate (BVA) and Principal Component Analysis (PCA) (Zhuang, Bradtmiller, and Shaffer 2007), are currently being used by the National Institute for Occupational Safety and Health (NIOSH) and ISO to ensure that a respirator fits 95% of the general population. Anthropometric measurements were performed on each subject to determine their fit test cell in both the bivariate and PCA fit test panels (Zhuang, Bradtmiller, and Shaffer 2007). The BVA and the PCA panels are represented by 10 and 8 test cells, respectively, where the larger numbered cells represent large size faces. Final distribution included bivariate cells 3,5,7,8,9 and PCA cells 1,5,6,7,8, showing more of a bias towards larger face size.

Each subject donned a single-use coverall (Kleenguard A60) and nitrile gloves in addition to their respirator. A probed N95 filtering facepiece respirator was chosen (either the regular size 3M 8210 or the small size version 3M 8110s) to fit the subject, and worn for 5 minutes to allow the mask to adjust to the face. A quantitative fit test (QNFT) was then performed using two Portacount Plus and N95 Companion instruments, as described above; the Canadian standard Z94.4-11 exercise protocol was followed, which consists of seven 30-sec activities (normal breathing, deep breathing, turn head side-to-side, nod head up-and-down, slowly recite alphabet, bend over once every 2 seconds, normal breathing) (CSA 2011a). The suit hood was not donned during the QNFT.

If the subject did not achieve a fit factor of at least 100 during the QNFT, they were re-tested with a respirator of a different size. In some cases, the test participant was re-tested in the same respirator size used initially, if an inappropriate donning of the mask or other error was suspected.

Simulated Workplace Protection Factor Test (SWPF)

Prior to beginning any tests, each subject was walked through all 15 activities to be sure they understood what they were expected to do. Following the QNFT, the subjects completed donning the full ensemble by placing the hood of the coverall over their head. The SWPF routine took place immediately following the initial QNFT without removing the respirator or any of the tubing. Clocks were synched between the two operators and the 31-min SWPF routine was begun (Table I) using the double Portacount methodology described above.

Final Quantitative Fit Test

Nine of the 11 subjects performed an additional quantitative fit test immediately following the SWPF. Subjects 1 and 4 did not complete a QNFT after the SWPF and therefore only have a single QNFT measurement. Subjects were instructed to remove the hood of their suit prior to starting the second QNFT. This second QNFT was performed in exactly the same manner as the preliminary fit test following the Canadian standard Z94.4-11 (CSA 2011a) and using the double Portacount methodology.

Data Analysis

All data were checked for normality and then log-normality using a Shapiro-Wilk test. Second-by-second fit factors were calculated by dividing the ambient (challenge) concentration by the concentration inside the respirator facepiece. The initial and final QNFTs were calculated by taking the geometric mean of all the second-by-second fit factors for the QNFT.

Exercise-specific SWPFs were determined by taking the geometric mean of the second-by-second fit factors for each exercise. The overall SWPF was calculated by taking the geometric mean of all of the fit factors for all exercises combined. Descriptive statistics were used to examine the geometric means of the SWPF data including box and whisker plots which show 1st and 3rd quartiles and median indicated by a line in the middle. Bar graphs were used to determine, by activity, how many of the subjects achieved a SWPF greater than 500; this cut point was chosen to accentuate exercises where subjects achieved the lowest fit.

A paired t-test was used to compare geometric means from the first repetition of exercises for all subjects to the second repetition of all exercises for all subjects. A Spearman's rank correlation coefficient was used to compare SWPF to initial and post QNFT. Box plots comparing the fit factors experienced during the 5 normal breathing exercises throughout the SWPF routine were constructed to visualize how fit, overall, changes with time. Additionally, a repeated measure ANOVA was used to determine if there was a difference between normal breathing repetitions for all subjects.

RESULTS

Using the Shapiro Wilk test, all subject fit factors were determined to be log-normally distributed. Two subjects (3 and 7) achieved an initial quantitative fit factor of at least 100 with the small size respirator while the remaining subjects wore the regular size. Two subjects (1 and 4) completed only an initial fit test; the remaining 9 subjects completed quantitative fit tests before and after the SWPF test. Initial fit factors ranged from 147 to 1708 (median = 432); final fit factors ranged from 75 to 2419 (median = 432) (Figure 1).

All subjects successfully completed the 31-min SWPF routine while wearing the N95 respirator, suit and hood, and gloves. The median SWPF for all activities was greater than 100 for all but two subjects (7 and 8) (Figure 1). For the nine subjects completing both QNFT tests there was no clear trend in the initial and final FF. For three subjects (3, 8 and 11) the FF decreased after the SWPF test; the FF improved after the SWPF test for two subjects (5 and 9), and the FF was similar before and after the SWPF test for four subjects (2, 6, 7, and 10). For two of the subjects with lower post-SWPF fit factors (8 and 11) the second FF was less than the US and Canadian requirement of 100 (Figure 1).

For most subjects (7 of 11) the geometric mean overall SWPF ranged from 100 to 1000 and their initial and final quantitative FFs were also clustered in this range (Figure 1). One subject (2) had an overall SWPF much greater than 1000 (mean = 3122); this person also achieved initial and final FF > 1000 (1135 and 1457, respectively). Two subjects (7 and 8) had overall SWPF well below 100 (42 and

57, respectively); their initial and final quantitative FFs were among the lowest measured. While the average overall SWPF for subject 11 exceeded 100, the lower range fell below 100 and the initial and final FF were also among the lowest measured (134 and 69, respectively).

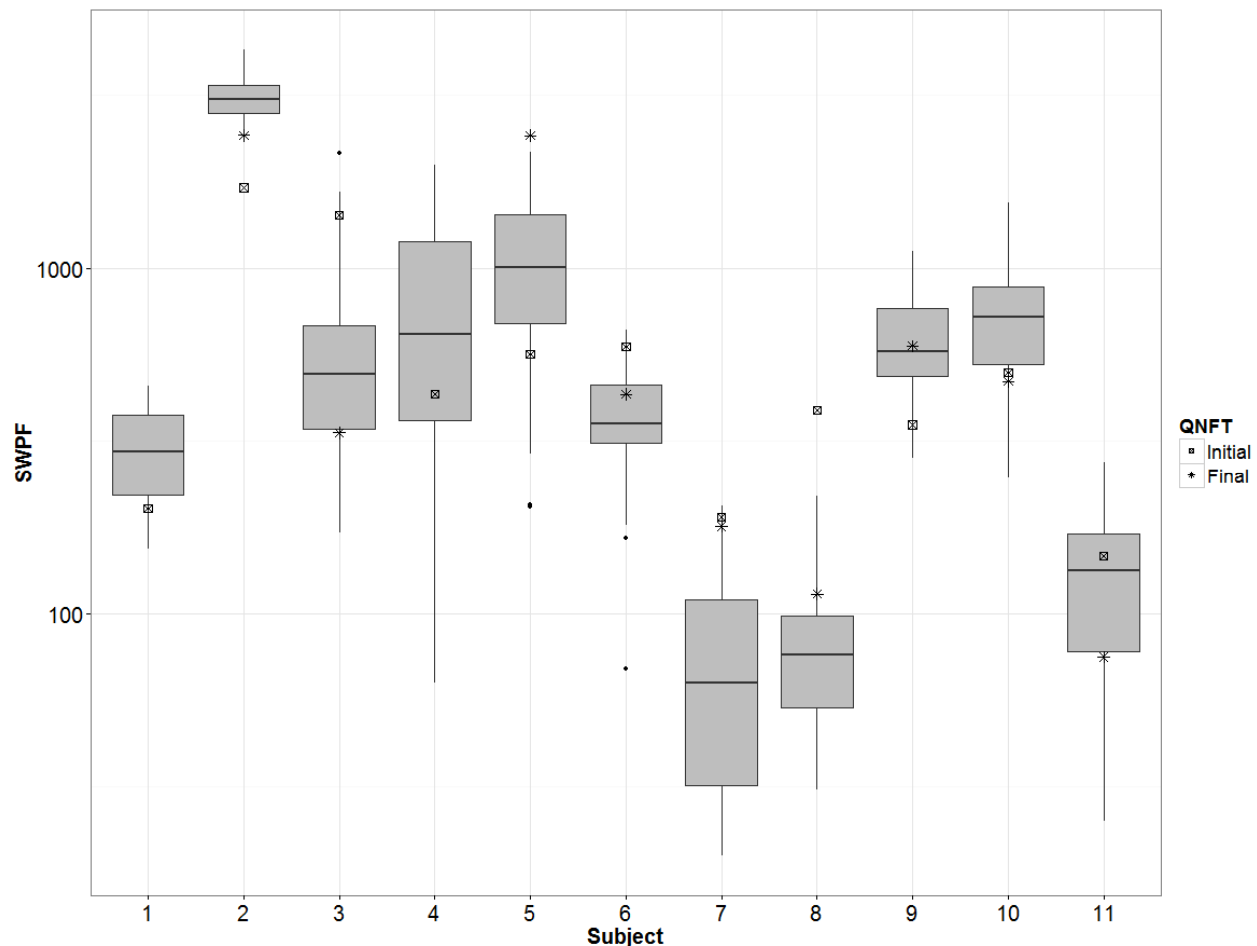


Figure 1. Initial and Final Fit Factors and Simulated Workplace Protection Factors by Subject.

For some subjects, donning the hood after the initial QNFT did not affect the fit of the respirator (6 and 10). For subjects (2 and 7), however, the results were different. For subject 2 adding the hood of the single use coverall appeared to increase the protection the respirator provides. During the 31-min exercise routine the SWPF was much higher than either the initial or final FFs measured without the hood. For subject 7 the opposite was true -- the initial and final FFs are much higher than the SWPF, suggesting that the hood may have adversely impacted respirator fit when active. Subject 7 noted that the hood was tugging on the straps causing the mask to dislodge during the SWPF exercises.

For all subjects the exercises that involved facial expressions (smile, frown, yawn, and rotate jaw) and stepping onto a platform, raise arm to touch ceiling, small jump off platform, and touch floor with arm had the lowest exercise SWPFs (Figure 2).

While the initial QNFT was significantly correlated to SWPF ($r = 0.68$, $p\text{-value} = 0.025$), a stronger correlation was observed between the final QNFT and SWPF ($r = 0.92$, $p\text{-value} = 0.001$) (Table II). The

two QNFT values were not significantly correlated to each other ($r = 0.62$, $p\text{-value} = 0.086$). One subject's second-by-second SWPF shown over the 31-min exercise period (Figure 3) illustrates that the fit of the respirator was compromised during jogging and walking on the treadmill but improved during normal breathing immediately afterward.

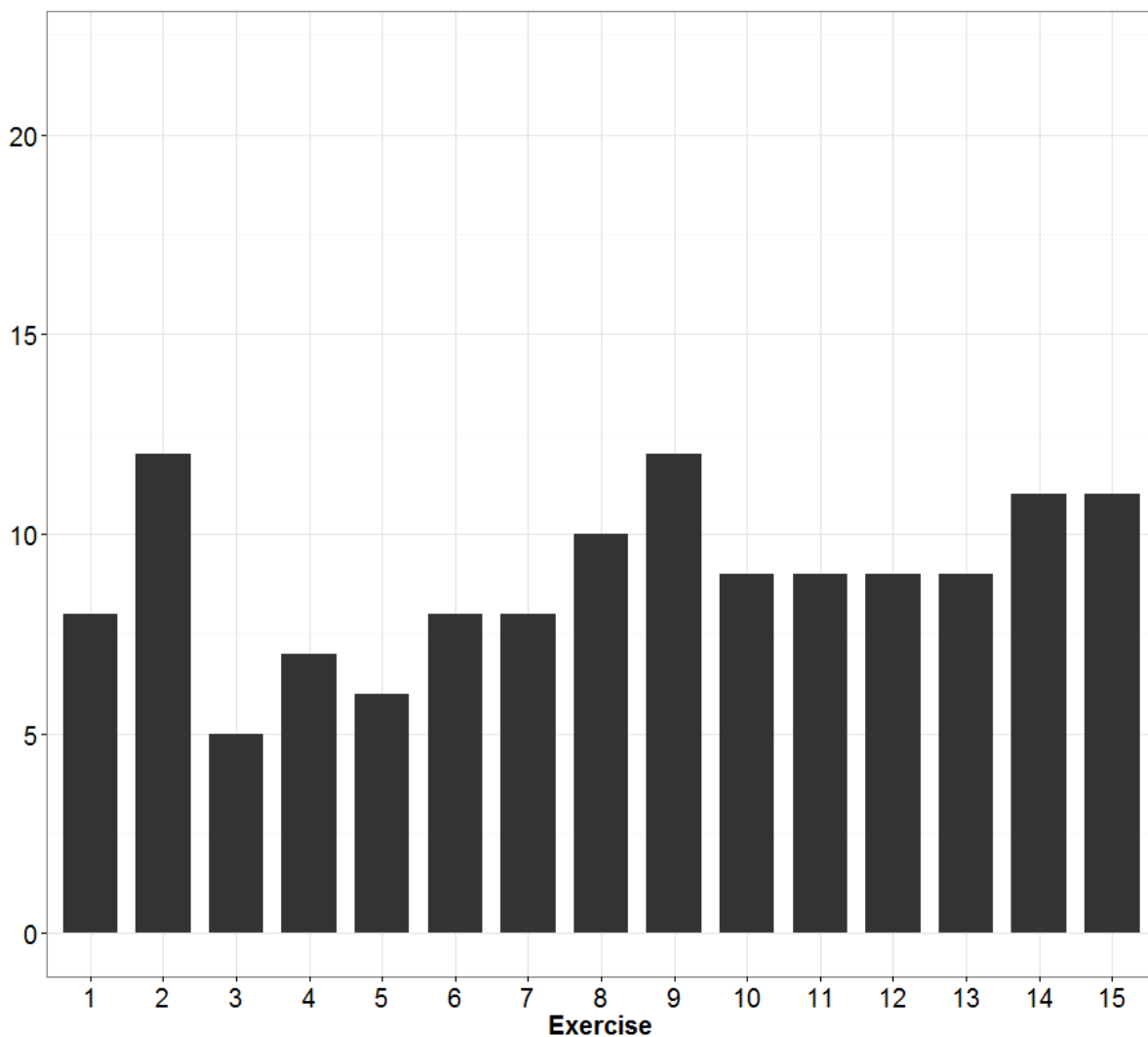


Figure 2. Frequency of SWPF > 500 by exercise for entire activity routine (refer to Table I for details on exercises) (maximum = 22; 11 subjects x 2 repetitions, final normal breathing is not shown).

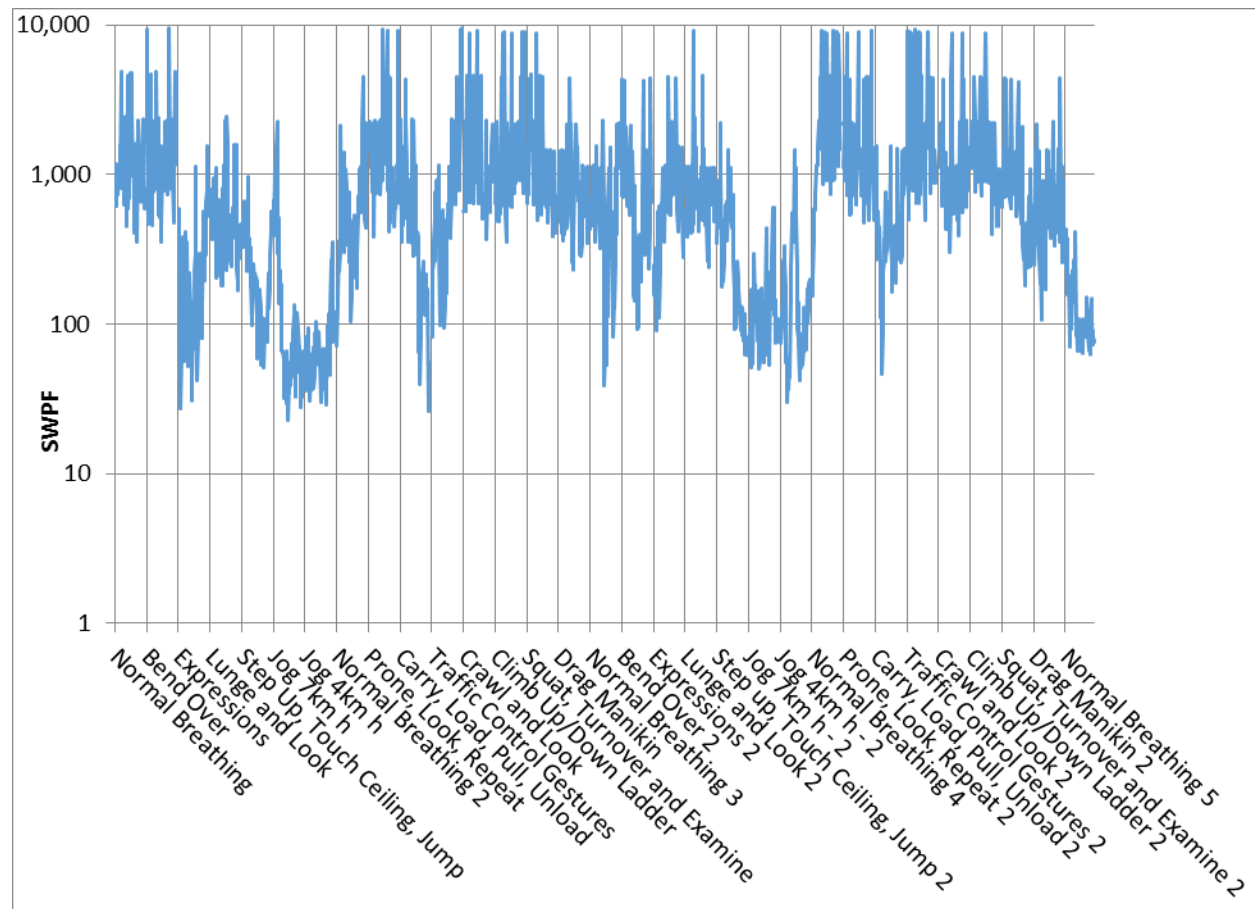


Figure 3. Example of Instantaneous SWPF for 30-min Activity Routine (Subject 4).

Box plots of exercise SWPFs by repetition (Figure 4) show that, in addition to decreases in SWPF for second repetition in later exercises, the second repetition exercise SWPFs were also more variable for many of the exercises. A repeated measure ANOVA did not identify any difference between normal breathing repetitions (p -value = 1.00), which can also be seen graphically in Figure 5.

DISCUSSION

The fit of an N95 respirator during these SWPF exercises appears to be person-specific and our data suggest that the initial QNFT with a limited set of short exercises is less predictive than the final QNFT. We cannot say for certain, however, whether this might also be due to the fact that the full ensemble (i.e. hood) was not worn during the initial QNFT. That the final QNFT was highly and significantly correlated with the SWPF, although the hood was again not worn, suggests that wear time may also be important in establishing a representative fit prior to conducting a fit test.

Our data also show that repeated sets of activities in combination with second-by-second measures of fit can illuminate which work activities are most likely to cause the SWPF to drop as a result of respirator movements on the face, higher inward air flow during heavy work, sweating, or a combination of these.

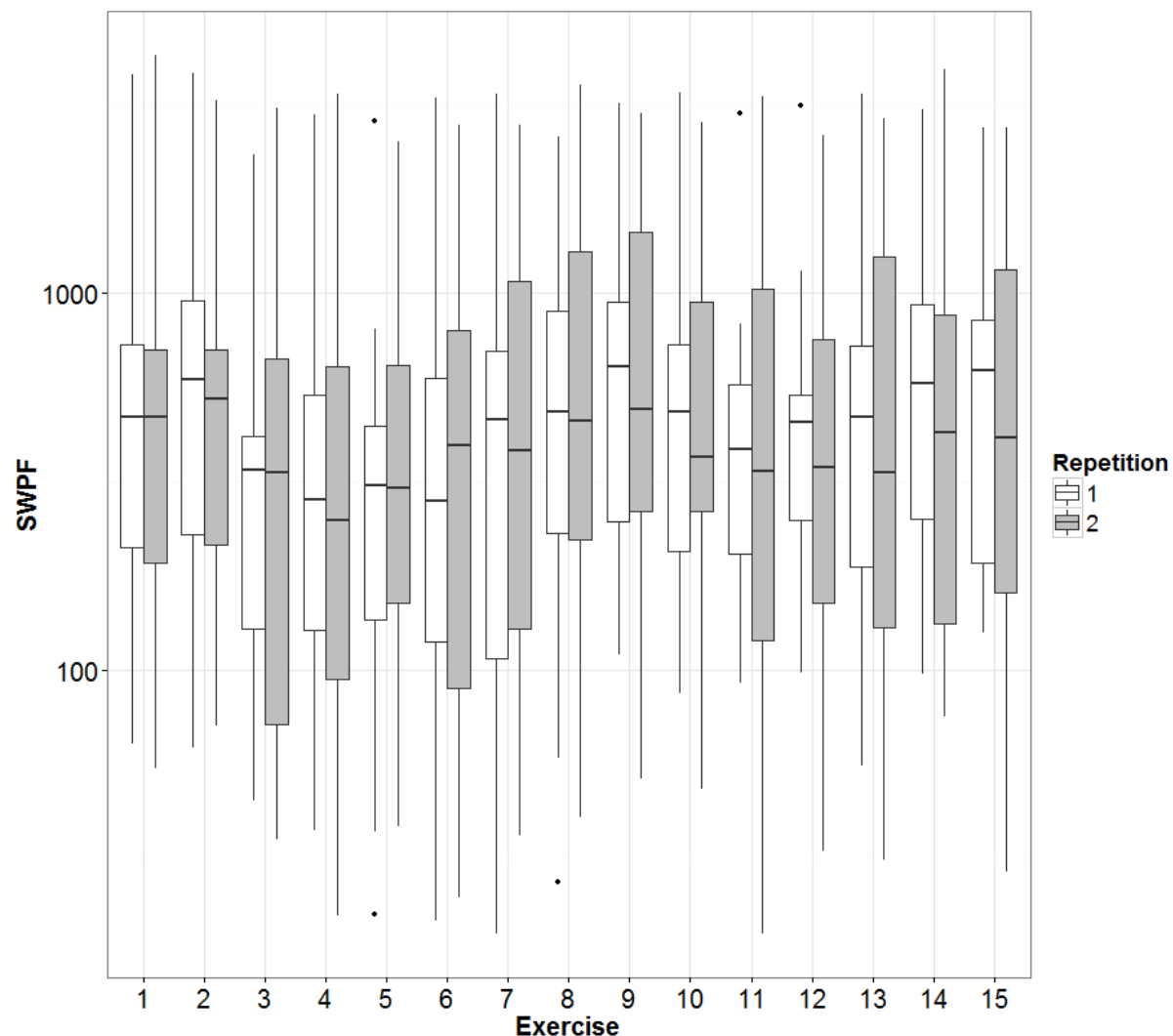


Figure 4. Each exercise SWPF by repetition for all subjects combined (n=11) (refer to Table I for details on exercises).

First responders are often required to wear multiple levels of personal protective equipment (PPE). Both the US Standard as well as the Canadian standard require all PPE that would be worn while someone performs their job be donned during the fit testing procedure (CSA 2011a; OSHA 1998b). While the Canadian standard describes the effect of multiple PPE layers, neither standard addresses how well the respirator will function in a realistic workplace scenario.

The Canadian QNFT protocol can be completed in about 4 minutes and includes exercises (normal breathing, deep breathing, head side-to-side, head up-and-down, reciting the alphabet, bending over, and normal breathing) that have been found by others to be effective at identifying poorly-fitting respirators (Crutchfield, Fairbank, and Greenstein 1999; Richardson et al. 2014). However, there have been few direct comparisons between QNFTs and WPFs – simulated or otherwise. In the future, we recommend that similar SWPF studies should evaluate initial fit with and without the full ensemble. This might capture initial ensemble effects that could be remedied with different sizes or designs. As well, it

would elucidate whether decreased respirator performance is due to the ensemble or other effects, such as sweating and/or breathing rate.

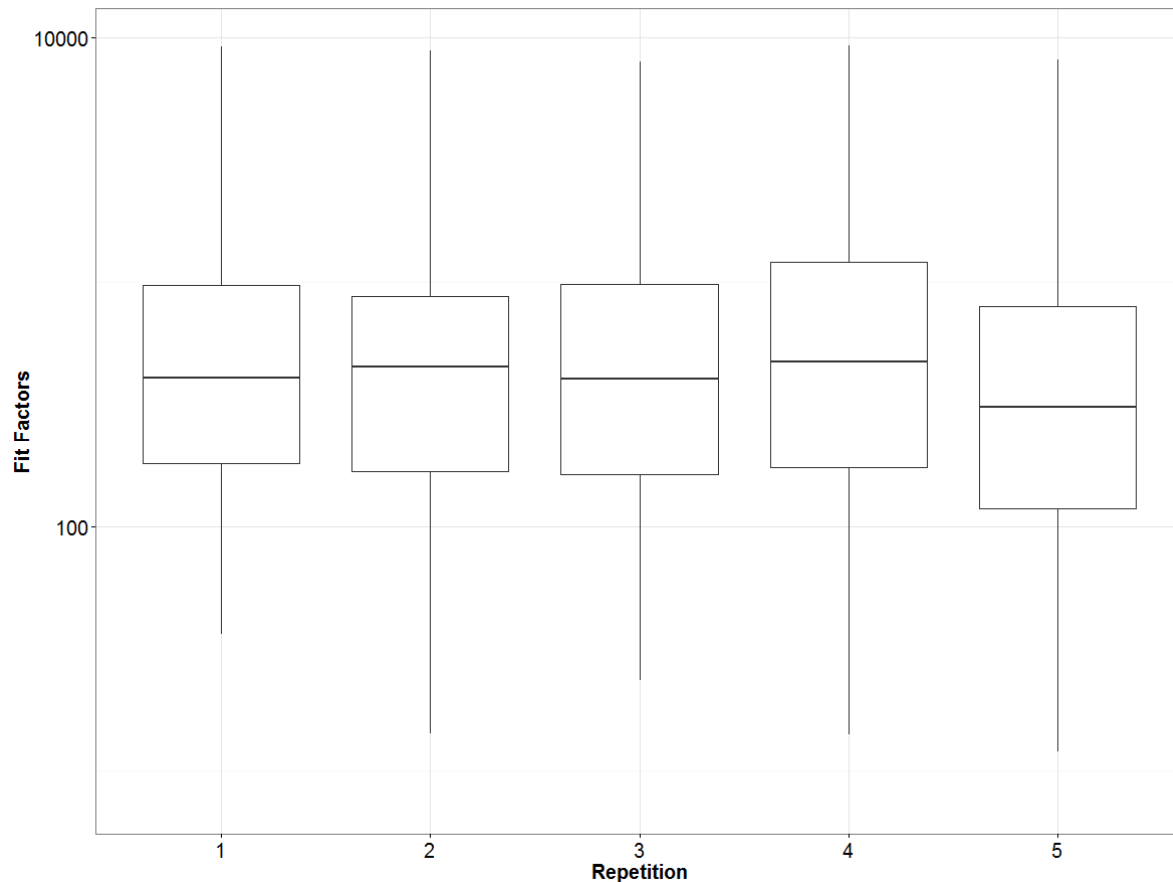


Figure 5. Normal Breathing boxplot by normal breathing repetition (n = 11).

It should be noted, as well, that for an SWPF protocol to be considered validated, we would need to compare respirator fit during real work activities. For first responders this is not yet possible with our current technology. We expect, however, that with on-going trends toward miniaturization of instruments and wireless data collection, such validation will be possible in the near future.

There are a few limitations that should be noted. This study had only 11 subjects, whose facial measurements did not include all cells in the NIOSH bivariate or PCA panels. It was particularly difficult to find enough emergency responders with smaller faces, because the population is predominantly male. A broader range of face sizes would have allowed us to identify more specific trends and reach more firm conclusions; various standards suggest upwards of 25 subjects to get a more complete distribution. (NIOSH 2003; CSA 2011b).

Face-seal leakage can often occur quickly and for short amount of time, making it sometimes difficult to notice when respirator performance was adversely impacted by an exercise during a SWPF test. The RMCC software has been recently updated and now allows on-going observation using a real-time plot of the SWPF, which may further assist in elucidating exact points at which respirator fit decreases along with the specific activities responsible.

Each subject was interviewed by an investigator after completing the final QNFT. Subjects were asked whether they noticed anything about their respirator, ensemble or test conditions that might have affected respirator fit. There was no interview protocol, or requirement that subjects respond to these questions. In future research we recommend including a written survey or interview after each SWPF trial, provided for familiarization before the trial, which might include questions such as the following:

- When did the subject start sweating?
- During which (if any) exercise did they notice the respirator fit change?
- Did they feel the coverall suit pulling on the respirator in any way?
- Did the fit at the end feel similar to the fit at the beginning of the trial?
- Did they have to adjust the respirator at any time during the trial?

CONCLUSIONS

First responders are often required to work long shifts while wearing respirators. Depending on the required level of protection, they might be expected to wear a full facepiece respirator. There are disadvantages to this type of respirator, including greater physiological and psychological stress, limited field of view (e.g. for paramedics needing to perform medical procedures on injured victims), and more difficulty with communication (e.g. for police public order responsible for crowd control), which may limit their ability to work safely or for long periods of time. Some subjects in this study were observed achieving high levels of protection when wearing an N95 filtering facepiece respirator as part of a relatively low level protective ensemble. As well, we have demonstrated that the SWPF protocol offers important insights into respirator fit over time using realistic simulated activities. It may be possible, in time, to employ such protocols in lieu of combining an assigned protection factor with a QNFT, for selecting an appropriate respirator and other PPE.

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