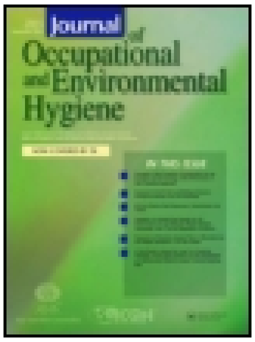

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Performance of a Novel Real-Time Respirator Seal Integrity Monitor on Firefighters: Simulated Workplace Pilot Study

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ABSTRACT

Millions of workers, including firefighters, use respiratory protective device. The key aspect in assuring the intended protection level of a respirator is its fit. However, even if the respirator originally fits well, the faceseal may be breached during its use. Until now, there have been no practically viable, inexpensive means to monitor the performance of a respirator during actual use. A novel Respirator Seal Integrity Monitor (ReSIM) was developed and recently evaluated on manikins by our team. The objective of this study was to evaluate the ReSIM effectiveness on respirator-wearing firefighters exposed to aerosols while performing simulated routine operational activities. Initially, fifteen subjects were recruited for the study. Following a preliminary investigation that resulted in modifications in the ReSIM prototype and testing protocol, a subset of nine firefighters was chosen for a full-scale evaluation. The testing was conducted in a 24.3-m^3 exposure chamber using NaCl as the challenge aerosol. Controlled faceseal leaks were established by opening a solenoid valve for 10, 15 or 20 seconds. Leaks were also established as the tested firefighter slightly repositioned the respirator on his/her face. During the testing, the ReSIM measured particles inside a full-face elastomeric respirator with a 72.7% leak detection sensitivity (probability of correct leak identification) and an 84.2% specificity (probability of correct identification of the intervals which are absent of any leak). After adjusting for false negatives and persistent false positives, sensitivity and specificity increased to 83.6% and 92.2%, respectively. The factors causing minor limitations in leak detection sensitivity and specificity can be attributed to variability among subjects, moisture's effect on the particle sensor, and some in-mask sampling bias. In conclusion, the ReSIM can promptly detect the breach in a respirator faceseal with high sensitivity and specificity. Due to its capability to alert the wearer of possible overexposure to hazardous aerosols, the ReSIM concept has a remarkable potential to be applied in various working environments, where respirators are used.

Keywords
aerosol, elastomeric respirator, faceseal leakage, sensor, sensitivity, specificity

INTRODUCTION

Workers wearing respirators must perform fit testing before initiating the use of respirators at a workplace and regularly afterward[(1)] to ensure that the respirator fits well, thus provides the anticipated protection.[(2)] However, fit testing cannot ensure that the respirator seal is properly maintained during actual use. In fact, it is recognized that the integrity of the facepiece seal may be affected by workplace conditions. This is particularly true for firefighters who engage in strenuous activities involving aggressive body movements in all phases of firefighting. They often encounter hazards such as falling debris or sparks from a fire while maneuvering in tight spaces, and collide with immovable objects due to sight limitations while working in dark, smoky environments. This all offer plenty of opportunities for compromizing the integrity of the faceseal or inflicting damage on the respirator body or a filter cartridge that may dramatically decrease protection level of the respirator. Even a relatively short period of respirator performance failure, which often remains undetected, may lead to significant exposure to hazardous substances.

During fire knockdown (when visible flames are mostly extinguished) and overhaul (when hidden sources of combustion are searched for and put out) a mixture of toxic gases and particles are released into the surrounding air.[(3-5)] A typical structure fire may involve burning of plastics, foams, fabrics, carpets, asbestos-containing materials, and wood products.[(6)] Additionally, combustion of such as electronics and household cleaners can make the smoke especially toxic. Although fire overhaul activities reduce the amount of smoke, the levels of hazardous airborne substances may remain high, exceeding the occupational exposure limits.[(6)] Over 70% of particles originating from fire suppression are ultrafine particles,[(7)] which have a potential to induce adverse health effects, such as impairment of cardiovascular function and cancer.[(8-11)]

Possible immediate effects following overhaul operations include changes in spirometric measurements and lung permeability.[4]

While firefighters involved in pre-overhaul operations (e.g., fire knockdown) must wear self-contained breathing apparatuses (SCBAs) to protect them from smoke and heat, there is no mandatory protection protocol for overhaul operations. This allows fire departments to set policies on use of various respiratory protective devices during overhaul operations. Correspondingly, it has been reported that firefighters use air purifying half or full facepiece respirators during overhaul.[4,5]

Recently, a novel Respirator Seal Integrity Monitor (ReSIM) capable of detecting a respirator's performance failure in real time was developed, and the prototype was evaluated under controlled laboratory conditions.[12,13] The ReSIM consists of a particle sensor PPD60PV-T2 (Shinyei, Kobe, Japan) utilizing optical light scattering principle, data acquisition and processing core, an air pump, supporting electronics, and an alarm system. The main idea of the ReSIM is to monitor the in-mask concentration of relatively large particles ($\gtrsim$ 0.5 μm), which essentially do not penetrate through a typical high-efficiency filter such as P100.[14,15] Thus, if these particles are present inside the respirator in significant counts, one can suppose that they entered the respirator through a faceseal leakage. The ReSIM does not directly measure particle concentration. Instead, its output is the percentage of time the sensor detects particles during a reporting interval (30-s), which is referred as Pulse Occupancy Ratio (POR, %). POR is directly correlated with the particle concentration. An important feature of the ReSIM is its capability to trigger an alarm once a leak is detected. A 3-step leak detection algorithm, which is described in detail elsewhere,[12,13] is optimized based on the actual test results and can be further modified.

Based on prior evaluation in laboratory settings,[13] the ReSIM was found capable of measuring the aerosol concentration in a relevant particle size range. Experiments involving elastomeric half-face respirator donned on a manikin demonstrated that the ReSIM could rapidly detect a faceseal leakage with high sensitivity and specificity when challenged with NaCl or combustion aerosols. This study aimed to evaluate the performance of the novel ReSIM on human subjects. The testing was performed with firefighters engaged in their routine operational activities, simulating a fire overhaul.

MATERIALS AND METHODS

Recruitment of Human Subjects and Preliminary Testing

The study protocol was approved by the University of Cincinnati Institutional Review Board (IRB). In total, 15 human subjects were recruited for the study. Before testing, each subject was medically cleared to wear a full-face respirator and signed the informed consent form.

In the preliminary effort, six respirator-wearing subjects were tested with the ReSIM. Resulting from this effort some challenges were implemented to the ReSIM prototype previously tested in the laboratory.[12,13] Additionally, the originally developed testing protocol was slightly modified. Specifically, a moisture trap was designed and integrated into the sampling train. The water vapor exhaled by a subject was observed to condense in the sampling train, which could have led to particle losses in the aerosol sampling line between the in-mask sampling port and water condensation on the ReSIM detector, thus potentially affecting the ReSIM performance. Furthermore, moisture in the sampling train might have interfered with the ReSIM's electronics. It has been shown that the presence of water vapor may cause an overestimation of particle concentration, or a failure in the circuits of the particle sensor resulting in measurement bias.[16]

Following the above preliminary evaluation, a subset of nine firefighters (different from subjects participated in the preliminary testing), including seven males and two females, was subjected to a full-scale testing utilizing the final ReSIM prototype and the modified testing protocols. The subjects had a variety of facial dimensions and configurations representing different categories of the National Institute for Occupational Safety and Health (NIOSH) bivariate panel.[(17)]

Test Set-Up

During the tests, firefighters used an elastomeric full-face respirator (6000 series, sizes S, M, and L, 3M Corp., St. Paul, MN, USA) equipped with two NIOSH-certified P100 filters (Model: 2091, 3M Corp., St. Paul, MN, USA). The full-face respirator was chosen because all firefighters in our study widely deploy it during overhaul operations. To ensure a proper respirator fit, the subjects used the same size respirator as they were provided on the job (and annually fit tested with[(1)]), and the real-time fit was verified (i.e., no particles were detected inside the respirator) with the reference aerosol instrument prior to testing (explained below).

The respirators were modified for this study. Two adapters were fitted to the mask, one each between the P100 filters used in testing and the filter mounting ports on the mask (Figure 1). One adapter contained a solenoid valve (G3315-S14, Precision Dynamics Inc., New Britain, CT, USA) controlling a 2-mm diameter orifice. When opening the valve, outside air could enter the respirator to induce artificial faceseal leakage, whereas closing the valve, the respirator remained properly sealed. Aerosol sampling was conducted through the other adapter of the same type that was attached to the other side of the respirator allowing a sampling tube enter into the mask (Figure 1).

During each test, a subject was asked to wear his/her turnout gear, including boots, protective pants, and a jacket (Figure 1). Helmets were not included as they would potentially interfere with Tygon sampling tubes during testing.

The testing was conducted in a 24.3-m^3 exposure chamber. The challenge aerosol, NaCl, was generated using a particle generator (model 8026, TSI Inc., Shoreview, MN, USA). An Optical Aerosol Spectrometer (OAS, Model 1.108, Grimm Technologies, Ainring, Germany) was used as a reference instrument to confirm the changes in detected particle concentrations inside the respirator during leak and non-leak intervals were consistent with ReSIM readings. The OAS was also used to verify that minimal number of particles were detected when the respirator's face seal was intact. The ReSIM and OAS were connected to the same sampling tube drawing air from inside the respirator (Figure 1).

Test Protocol

The NaCl challenge aerosol was generated in the chamber for at least 15 minutes before testing and the generation continued during testing. At the beginning of the test, the subject breathed normally for 2 min, after which he/she stepped up and down a stepstool to represent the most common activity executed during an emergency response, climbing stairs. Respirator leaks were simulated in every two minutes, when a test operator pressed the control valve to open the orifice for 10, 15, or 20 seconds (Figure 1B). Each duration of leak was simulated in 3-10 replicates in random order during each test. The respirator remained fully sealed when the valve was closed. Additionally, each subject created a leak with two replicates by re-adjusting/re-positioning the respirator on his/her face (which is often done in the field). There was a break after each 15-20 min of testing; during these breaks the subjects were provided with water and the opportunity to cool down while partially taking off the uniform. Extra breaks were offerred on subject's request.

Leak Detection Algorithm

In this human subject testing, the leak detection threshold values for each ReSIM data processing interval were calculated based on the following equation:

$$t = max\{k \times r_{avg}, c\} \quad (1)$$

where t is the leak detection threshold in percent; k and c are semi-empirical constants which are specific to a challenge aerosol and ambient concentration (k=1.2 and c=1.2% for NaCl aerosol); r_{avg} is the rolling average of the POR (%) for the previous five intervals not identified as having a leak. According to this equation, a leak must induce POR of at least 1.2% of the current 30-s interval to be considered a leak. On the other hand, the minimum increase in POR required to be detected as a leak is 1.2 times the rolling average of the previous five background intervals not identified as leaks. In practice, a higher value of 1.2% (or 20% above the rolling average) was selected as the leak detection threshold value for each 30-s interval.

Note that the lower POR limit of the leak detection (i.e., t) obtained in this study (1.2%) differs from the one reported in our previous manikin-based study (2%).[13] It is acknowledged that the former was calculated for NaCl while the latter originally derived from experiments conducted with combustion particles. The quoted study revealed that the ReSIM performance with respect to leak detection (sensitivity and specificity), was dependent on the particle composition and background aerosol concentration level. As the particle sensor of the ReSIM utilizes the optical particle detecting principle, the variability of refractive index among particles of different composition affects the sensor-generated measurement result.[16] Further, the in-mask aerosol concentration should follow the ambient background level, given all other conditions are the same. Therefore, the sensor detection capability must be greater at higher ambient concentration. Based on the above, the leak detection algorithm was adjusted to NaCl as the challenge aerosol and to the ambient background concentration of 128 – 736 particles/cm^3 used in this study (for the size range of 0.5 – 2 μm).

Statistical Analysis

ReSIM's performance detecting the leaks were evaluated by determining its statistical sensitivity and specificity similar to Wu et al.[(13)] Sensitivity refers the ability of the ReSIM to correctly detect the leaks (true positives). False negatives occur when ReSIM fails to detect a leak, while it is present. Specificity refers the ability of the ReSIM correctly identifying intervals without leaks (true negatives). False positives occur, when ReSIM's response is positive (a leak is detected), although no leak actually occurred. The two performance quantifiers are determined as follows:

$$\textbf{Sensitivity} = \frac{\textbf{True Positive (TP)}}{\textbf{TP}+False\ negative\ (FN)} \times 100\% \quad (2)$$

$$\textbf{Specificity} = \frac{\textbf{True negative (TN)}}{\textbf{TN}+False\ positive\ (FP)} \times 100\% \quad (3)$$

RESULTS AND DISCUSSION

The subject-specific results are presented in Figure 2. Ideally, the ReSIM response during non-leak intervals (quantified as POR and plotted as white bars) should stay below the leak threshold limit (black dashed line). In presence of a leak (black bars), POR should exceed the leak threshold limit demonstrating that ReSIM detected the leak. It was observed that the ReSIM data differed considerably from one subject to the other. The POR measured during leaks varied from 0.03 to 20.4%. The ReSIM response was most distinct for firefighters #4 and #8 and the lowest for firefighters #2, #3 and #9. Since, as was reported earlier, the ReSIM response directly correlates with the particle concentration,[13] the POR fairly well reflected the particle concentrations inside the mask. The concentration measured by the OAS during the establishment of a baseline for the ReSIM (response during intervals with the absence of a leak) varied from 0 to 1 particle/cm^3. In some cases, the in-mask particle concentration during a leak remained at the baseline level (i.e., <1 particle/cm^3). Sometimes this low concentration determined during a leak triggered the ReSIM response, but on other occasions those leaks remained undetected by the ReSIM (marked as grey bars in Figure 2). These low, close-to-background particle concentrations were likely insufficient to be able to trigger the ReSIM alarm. This raises the question as to whether the leak was successfully introduced. The between-subject variability in the particle concentration and ReSIM responses was very distinct when compared subjects #8 and #9, who were tested under virtually the same conditions. For firefighter #8, the leaks were all introduced successfully and detected correctly, but for firefighter #9, the particle concentration inside the respirator remained too low during seven leaks, with only three leaks identified correctly.

Differences in breathing flow rate and breathing pattern, as well as in facial dimension among subjects likely contributed to the data variability. Additionally, human subjects introduce factors, such as sweating and air supersaturating during exhalation, which can lead to condensation inside the sampling line and consequently cause sample transmission errors.[18] Furthermore, penetrating particles do not necessarily mix well within the cavity of a respirator (which is itself dependent on the subject's facial structure).[19] This may have formed variations in in-mask concentrations and, consequently, to the ReSIM's responses among subjects.

For subject #2, the respirator provided an outstanding level of protection with very low particle concentrations measured inside the respirator with no leak (0-0.16 particles/cm^3). As shown in Figure 2, the corresponding PORs of the ReSIM for intervals with no leak was extremely low, even down to 0% (white bars), except for the intervals immediately following a leak (see black bars). The PPD60PV-T2 particle sensor used in the ReSIM has limitations with respect to accuracy and sensitivity at very low particle concentration levels,[(16,20)] which may explain why the ReSIM did not always detect the leak. Specifically, at very low particle concentrations, the likelihood of a particle being in the detection volume decreases so that detection becomes a stochastic process with the chance of successive intervals containing no particles increasing as particle concentrations decrease.

Although a moisture trap was integrated into the sampling train during early testing to avoid moisture-related problems, some residual moisture was present, especially when testing firefighters #5 and #7. This can be seen from the Figure 2, when the POR is increased during non-leaks at the end of testing causing false positives. An earlier study has demonstrated that moisture can affect performance of the PPD type sensor.[(16)]

The testing protocol was altered to include the cases when a firefighter repositioned his/her respirator in a manner consistent with the field practices. Testing showed that particle concentration inside the respirator increases substantially during this repositioning. Typically, the particle concentration and ReSIM responses were higher during these self-adjustment periods as compared to the controlled leaks introduced by the test operator. The sizes, shapes, and duration of the leaks created by firefighters varied, whereas the controlled leaks were always similar (size: 2-mm diameter; shape: close to circular; duration: either 10, or 15 or 20 s).

The leak threshold limit remained 1.2% most of the time. It increased after breaks, when the ReSIM was exposed to high ambient particle concentration (see Figure 2, subjects #1 and #3) and due to condensation (subjects #5 and #7), which drove up the rolling average of the POR.

Sensitivity

The initially calculated overall sensitivity was 72.7%; 117 out of 161 intervals with true faceseal leaks were correctly identified by the ReSIM. There were 44 false negatives in total, when the ReSIM did not detect a leak, although it was present. Twenty-one of those false negatives were attributed to too low in-mask particle concentration. This may be due to subject-related factors (facial dimensions, breathing rate) or non-uniform particle distribution inside the mask. After excluding these data points (because they were associated by the experimental methodology, and do not reflect the ReSIM's ability to measure leaks), the sensitivity reaches 83.6% (adjusted value). Sensitivity varied greatly between subjects; the adjusted value ranged from 33.3% (firefighter #9) to 100.0% (firefighters #4 and #8), as indicated in Table 1.

For reference, in the previous study, in which the ReSIM's performance was evaluated using manikin-based set-up,[(13)] the sensitivity was 71.8% when tested with the same challenge aerosol as in the present effort (NaCl particles) and 98.4% when tested with combustion aerosol. A higher sensitivity for NaCl particles observed in this investigation is probably due to the lower leak detection threshold (1.2% compared to 2% in the manikin-based study[(13)]).

Like in the manikin-based study,[(13)] most of the ReSIM outputs of false negatives (true leaks that failed to be identified) differed from the baseline, but at the same time were very close to the leak threshold level (Figure 2). As discussed by Wu et al.,[(13)] the leak threshold limit can be further optimized. Based on this study, it is suggested, that the threshold level should, ideally, be designed for an individual subject. It is likely that the between-subject variability with respect of the threshold is not too high. Further studies should be performed to address this issue.

Specificity

Overall, ReSIM exhibited a rather high specificity (response to the absence of leaks): 84.2%, see Table 2. Data variability was not as distinct as observed for sensitivity, the specificity between subjects varied from 63.8% (#7) to 98.6% (#9).

Similarly to the previous study performed with the manikin set-up,[13] a persistent response to a leak over one or more intervals following a true leak was observed for most of the subjects. The effect was especially pronounced for subjects #4 and #8, which can be seen from the Figure 2, when a detected leak (black bar) is followed by a persistent false positive (white bar exceeding the leak threshold limit). In total, there were 59 persistent false positives. The respirator wearer would already be alerted by the actual leak, and these persistent responses only lengthen the duration of the alarm. Thus, the outcome should be adjusted by excluding those. With this adjustment, the overall specificity was 92.2% (Table 2).

As discussed earlier, moisture condensation induced false positives for subjects #5 and #7. Altogether 25 moisture-related false positives were observed (9 for subject #5 and 16 for subject #7). After excluding them, 24 false positives were observed. Eleven were observed for subject #7, and for other subjects, 0-4 random false positives were detected. This rather high specificity indicates that the ReSIM only rarely produced false alarms based on its operation.

In the manikin-based setup, specificity was 96.9% for both NaCl and combustion aerosols. After adjusting for persistent false positives, this laboratory-determined specificity increases to 99.8%.[13] It is acknowledged that the complexity related to human subject testing leads to the lower specificity observed in this study. One could anticipate that some of the positive responses of the ReSIM were not associated with the leak introduced by the test operator, but instead reflected presence of natural faceseal leaks (those may occur when respirator is donned on a subject, but are non-existent when the respirator is fully sealed on a manikin). The measurements conducted inside the respirator with the OAS ruled out this possibility.

It should also be noted that different respirators were used in this study and in the previous evaluation that involved manikins:[13] full-face respirators were used in this study and half-face in the previous one. In addition, the half-face respirator was fully sealed with a sealant onto the manikin's face, thus making the seal substantially better than that of the full-face respirator on a subject. Furthermore, the sampling line of the ReSIM was notably longer (~ 1 m) in this study as compared to 0.1 m established by Wu et al.,[13] which might have increased the particle losses. Thus, some of the differences observed in these two investigations may be attributed by different types of respirators used and the length of the ReSIM's sampling line.

One may speculate that during fire overhaul the aerosol concentration may be insufficiently high for the ReSIM to operate due to high amount of water in the air. However, the data reported from measurements conducted during fire overhaul operations suggest high concentration levels: the total and respirable dust mass concentrations of up to 30.79 mg/m^3 and 25.7 mg/m^3, respectively[6] and the particle number concentrations of, up to 2.11x10^6 particles/cm^3, on average.[7] This said, the high amount of water vapor may affect the performance of the ReSIM,[16] and it is recognized that the effect of hot and humid environment on the ReSIM's performance should be investigated.[13]

Future Directions

As a limitation of this study, it was observed that the current ReSIM prototype has moisture-related issues. While the moisture trap was integrated into the sampling train, the problem was not completely solved and some water droplets still condensing on the sensor could have affected the performance of the ReSIM (which was observed for two subjects). Furthermore, as discussed in this and the previous[13] papers, the leak detection algorithm and threshold could be further optimized to better represent differences among respirator users. In the future, the ReSIM prototype could be further improved by miniaturizing it and possibly making it fit inside the respirator. If the ReSIM is built inside the respirator cavity mask, the distance between the sensor and the wearer's mouth/nose would be negligible, thus reducing the condensation and particle wall loss problems.

Although the performance of the ReSIM was evaluated in this study with firefighters, the results could be applied to other work populations wearing elastomeric full-face respirators, such as workers exposed to asbestos[21] and lead[22] particles on the job. It is important to test the ReSIM with different workplace aerosols, because the ReSIM response is believed to be dependent on the aerosol composition. After evaluating the ReSIM with various aerosols, the resulting product could have an option to allow the respirator user to select the particle type (e.g., welding fume, combustion particles), against which he/she is protected by the respirator. Finally, the ReSIM should be applicable not only to elastomeric respirators tested in this study, but also to other types of particulate respirators, e.g., power air-purifying respirator. This, however, requires appropriate design modification and additional testing.

CONCLUSIONS

Testing with human subjects demonstrated that ReSIM prototype is capable detecting leakage in a respirator during routine operational activities performed by firefighters. Despite some challenges discovered during the testing with human subjects, the ReSIM showed high sensitivity and specificity and can alert a respirator-wearing worker about a sudden increase of his/her aerosol inhalation exposure due to the faceseal integrity failure. The ReSIM prototype can be further modified to make it more adaptive to various characteristics among respirator users. Future studies involving a greater number of subjects and/or different respirator models would help better understand the features of the new monitor and its applicability, including other types of particulate respirators and various workers' populations.

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Table 1. Sensitivity of leak detection for firefighters #1-9

Subject	Number of intervals with		Sensitivity (%) = $\frac{TP}{TP+FN}$	Number of intervals with too low C_{in}[B]	Adjusted sensitivity %
	True positives (TP)	False negatives (FN)[A]			
#1	14	1	93.3	0	93.3
#2	8	9	47.1	3	57.1
#3	15	4	78.9	1	83.3
#4	22	2	91.7	2	100.0
#5	7	10	41.2	6	63.6
#6	16	3	84.2	2	94.1
#7	15	2	88.2	0	88.2
#8	17	0	100.0	0	100.0
#9	3	13	18.8	7	33.3
All tests[C]	**117**	**44**	**72.7**	**21**	**83.6**

[A] False negatives occur when ReSIM's response is negative while a leak is present.
[B] The in-mask particle concentration (C_{in}) remained too low (<1 particle/cm^3) during a leak to be able to trigger the ReSIM response.
[C] Sum of all tests.

Table 2. Specificity of identifying intervals without leaks for firefighters #1-9

Subject	**Number of intervals with**		**Specificity % =** $\frac{TN}{TN+FP}$	**Number of intervals with**		**Specificity after adjustment %**
	TN[A]	**FP**[B]		**Persistent FP**[C]	**Adjusted FP**[D]	
#1	58	8	87.9	7	1	98.3
#2	58	7	89.2	4	3	95.1
#3	70	2	97.2	2	0	100.0
#4	78	15	83.9	14	1	98.7
#5	56	12	82.4	1	11	83.6
#6	63	10	86.3	6	4	94.0
#7	60	34	63.8	7	27	69.0
#8	62	19	76.5	17	2	96.9
#9	72	1	98.6	1	0	100.0
All tests[E]	**577**	**108**	**84.2**	**59**	**49**	**92.2**

[A] TN = True Negative means the respirator facepiece is fully sealed at 30-s intervals, and ReSIM does not detect a leak.
[B] FP = False positives occur when ReSIM indicate a positive response in the absence of a leak.
[C] A persistent false positive is a false positive occurring in the interval immediately after an interval with a correctly identified leak.
[D] Persistent false positives are excluded because the wearer would already be alerted by the preceding leak.
[E] Sum of all tests.

Figure 1. A firefighter performing testing. A: Firefighter steps up and down during the test: B: Respirator leaks were simulated by a test operator who pressed a switch controlling the solenoid valve to open it for 10, 15, or 20 seconds.

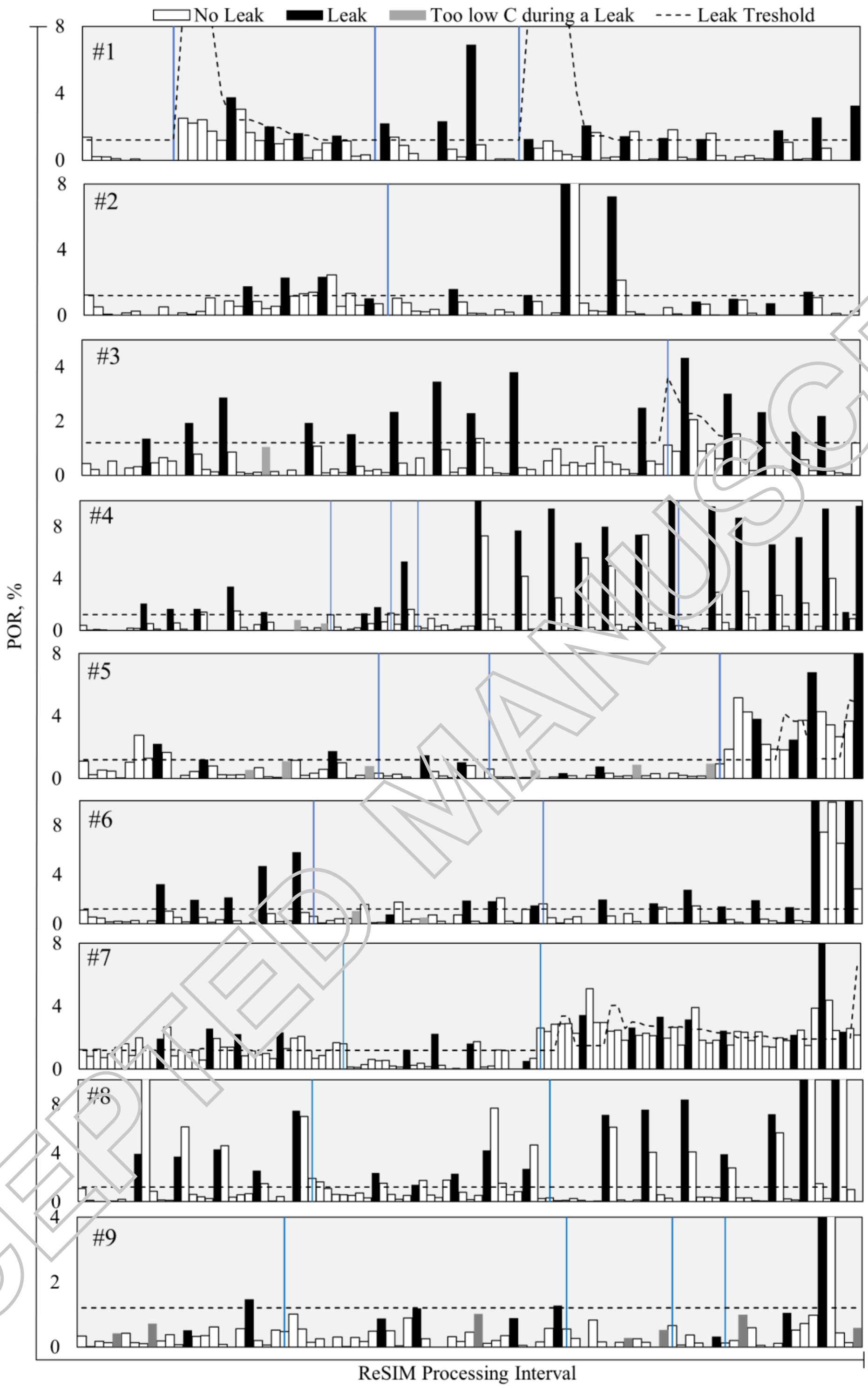

Figure 2. The Pulse Occupancy Ratios (%) from the human testing conducted with nine firefighters (#1-9). Results were obtained for subsequent 30-s ReSIM processing intervals throughout the tests while different leak conditions were created. Note the different scales of the y-axes for different subjects. Thin blue vertical lines point out breaks in testing, when firefighters removed their respirators.