Infrared Imaging for Leak Detection of N95 Filtering Facepiece Respirators: A Pilot Study

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Background *This study was undertaken to determine the utility of an infrared camera (IRC) for assessing leaks around filtering facepiece respirators (FFR) during quantitative respirator fit testing.*
Methods *Eight subjects underwent quantitative fit testing on six N95 FFR models (48 total fit tests) while simultaneously being recorded with an IRC.*
Results *The IRC detected 49 exhalation leaks during 39 tests and no leaks in nine tests. Exhalation leaks were identified in all failed fit tests (13) and a majority (26 of 35) of passed tests. Anatomically, the nasal region and malar (cheekbone) regions accounted for 71% of identified leak sites. Fit factors for fit tests without identified exhalation leaks were significantly higher than fit tests with leaks detected by IRC (P = 0.01).*
Conclusions *Thermal imaging using IRC can detect leaks in respiratory protective equipment and has the potential as a screening tool for assessment of the adequacy of post-donning FFR fit.* Am. J. Ind. Med. 54:628–636, 2011. *© 2011 Wiley-Liss, Inc.*

KEY WORDS: N95 filtering facepiece respirators; fit test; leaks; thermal imaging; infrared camera

INTRODUCTION

The sum total of leakage into a filtering facepiece respirator (FFR), termed total inward leakage (TIL), is the composite of leakage through (1) the face seal, (2) the filter element, (3) exhalation valves (for FFR that are so equipped), and (4) other sites (e.g., areas where straps, bands, etc. are connected to the FFR by staples or stitching, etc.) [Han and Lee, 2005]. Because face seal leakage is the major contributor to TIL [Clayton and Vaughan, 2005], the protection afforded by a FFR is significantly impacted by its fit; that is, the better the seal (fit) at the FFR/face interface (the rim of the FFR that is in contact with the facial skin), the (generally) greater the protection provided. Passage of an Occupational Safety and Health Administration (OSHA)-mandated FFR quantitative fit test (i.e., score ≥100, indicating ≤1% leakage into the FFR when comparing the ambient particle concentration with the within-FFR concentration) [US Department of Labor, 1998] indicates that a properly trained wearer in a respiratory protection program can achieve the level of protection assigned to that particular respirator, but does not imply that it is leak-free [Clayton and Vaughan, 2005]. This has important ramifications, for example, when dealing with biological agents that may require as few as one to three organisms to incite infection (e.g., influenza, measles, etc.) [Musher, 2003], and for which no generally recognized occupational exposure limits have been established, any leakage is potentially very important.

All objects (animate and inanimate) emit infrared radiation as a function of their temperature. This thermal energy can be visualized by an infrared camera (IRC) that

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captures infrared waves of electromagnetic spectra involving one of four bands [i.e., near IR (0.75 μm), middle IR (3–6 μm), far IR (6–15 μm), and extreme infrared (15–100 μm)] [Chekmenev et al., 2005]. The use of an IRC for measuring breath-related parameters is based upon the fact that the temperature of exhaled air is (generally) higher than that of the background of the typical indoor environment [Murthy and Pavlidis, 2006]. Thermal imaging inspections typically focus on surface temperature differences [Griffith et al., 2001] and the use of an IRC for detection of facemask leaks relies upon visualizing skin surface temperature changes occurring near the rim of the facemask that are brought about by the flow of exhaled gases through breaches in its seal [Kerl et al., 2004]. The temperature of the air expelled from a FFR has been shown to be lower than the temperature of the exhaled breath because of admixing with the (generally cooler) inhaled ambient air in the dead space of the FFR prior to expulsion [Monaghan et al., 2009]. This can result in either cooling or warming effects on the adjacent facial skin's temperature that is itself impacted by various factors (e.g., regional blood flow, ambient air temperature, sweating, etc.). Excellent correlations ($r = \geq 0.98$) have been noted between IRCs and hard-wired thermistors for skin temperature assessments [Herschler et al., 1992; Buono et al., 2007].

Limited investigation of the use of IRCs for detection of facemask leaks has identified exhaled air escaping from purposefully placed punctures in FFR [Dowdall et al., 2005] and has documented face seal leakage in respiratory therapeutic facemasks under continuous positive airway pressure [Kerl et al., 2004]. An IRC has also been used to monitor leakage from FFR adhesively mounted to a breathing mannequin headform [Monaghan et al., 2009; Roberge et al., 2010]. Identification of leaks occurring at the sealing surface (rim) of FFR during fit testing would allow for a more focused evaluation that could lead to improved engineering modifications (e.g., more adherent materials, inner flanges, etc.) or user alterations (e.g., molding the pliable nose wire to ensure a snugger fit, tightening straps, etc.) to improve fit and, by extension, enhance protection. This study was undertaken to determine the capability of an IRC for localizing FFR exhalation leaks during quantitative respirator fit testing.

MATERIALS AND METHODS

The study subjects included five men and three women experienced in the use of FFR; demographic data are found in Table I. The study was approved by the National Institute for Occupational Safety and Health (NIOSH) Institutional Review Board and all subjects gave verbal and written consent to be studied and recorded. All subjects had previously passed a standard eight-exercise OSHA quantitative respirator fit test [US Department of Labor, 1998] on the regular size of each of the FFR models to be studied. For each of the three models of cup-shaped N95 FFR investigated in the current study, subjects were tested in the regular size of N95 FFR that had been previously used to pass the standard OSHA fit test and the same N95 FFR in the small size, in order to maximize the (presumed) potential for leakage from the smaller size (8 subjects × 3 N95 FFR models × 2 sizes = 48 N95 FFR studied; FFR models are listed in Table II). None of the tested N95 FFR was equipped with an exhalation valve. Study N95 FFR were instrumented with a metal sampling grommet and donned as per the manufacturer's instructions (i.e., lower strap to back of neck, upper strap on crown of head). A shortened 121-second protocol utilizing the Portacount Plus® Model 8020A with N95 Companion™ accessory (TSI, Shoreview, MN), an optical counting device using condensation nucleus counting technology that calculates leakage as the ratio of within-FFR particle counts (C_{in}) to ambient particle counts (C_{out}) and has a maximum reportable score (fit factor) of 200 (irrespective of higher attainments), was used. The study

TABLE I. Demographics of Study Subjects (SD)

Subject	Sex	Age (years)	Height (cm)	Weight (kg)	Body Mass Index	Oral temp (°C)	NIOSH bivariate panel size[a]
1	M	42	173.0	95.3	31.8	36.44	5
2	F	33	166.1	106.1	38.5	36.88	3
3	F	40	169.4	112.0	39.0	36.38	4
4	M	26	175.5	71.1	23.1	36.83	3
5	M	47	190.7	98.1	27.0	36.60	6
6	M	42	174.7	79.5	26.0	36.61	7
7	F	39	171.9	84.1	28.5	36.72	3
8	M	38	181.9	119.2	36.0	36.38	6
Mean	n/a	38.3 (±6.3)	174.4 (±7.6)	95.6 (±16.6)	31.2 (±6.0)	36.60 (±0.19)	4.5 (±1.6)

[a]National Institute for Occupational Safety and Health respirator fit test panel utilizing face width and face length to determine facial size for appropriate respirator sizing [Zhuang et al., 2008].

TABLE II. Contingency Table of Subjects Passing and Failing the Fit Test With and Without Leak Detection by Infrared Camera

	Infrared camera		
Fit test	**Leaks**	**No leaks**	**Total**
Passed	25	9	34
Failed	14	0	14
Total	39	9	48

protocol, previously developed and used by Viscusi et al. [2010] to minimize subject test time when performing multiple donning fit tests, shares some features with other shortened protocols [Sreenath et al., 2001; Campbell et al., 2005]. The protocol has the subject perform only six test exercises as compared to the standard OSHA test which specifies eight exercises. Test subjects performed the exercises described in the standard OSHA protocol but for only 10 s each instead of the normal 60-s duration for each exercise. The test technician began each fit test by simultaneously starting the PORTACOUNT® and a timed PowerPoint® (Microsoft Corp, Redmond, WA) slide show used to queue the test subject of which exercise to perform. The six exercise sequence was: (1) normal breathing, (2) deep breathing, (3) move head up and down, (4) turn head left and right, (5) speak out loud (recitation of the "rainbow" passage), and (6) normal breathing. The first normal breathing exercise was longer (70 s) due to an additional amount of time required by the system to clear internal pathways of particles and measure the ambient particle concentration. The normal grimace and bending at the waist exercises were not included in this protocol in an effort to shorten the test time. The modified protocol calculates an integrated fit factor for the six test exercises (Fig. 1). This calculation method differs from the standard

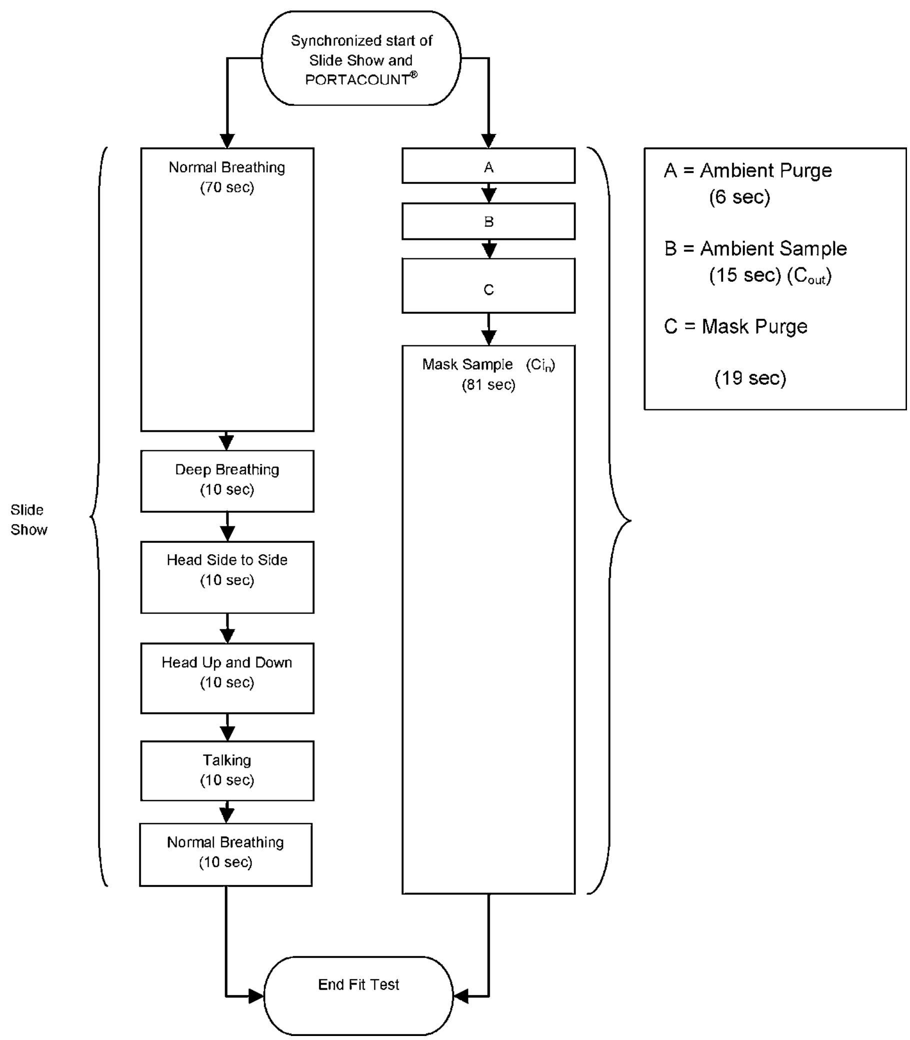

FIGURE 1. Abbreviated fit test protocol utilized in the present study. C_{in}, particle concentration in respirator dead space; C_{out}, ambient air particle concentration.

OSHA 8-exercise fit test method where the overall fit factor is calculated as the harmonic mean of fit factors obtained from seven of the eight individual fit test exercises (a fit factor for the grimace exercise is not included in the calculation). The fit factor for the modified protocol used was calculated as the ratio of the ambient particle concentration, $C_{(out)}$, which is sampled for 15 s divided by the mask concentration, $C_{(in)}$, which was sampled for 81 s (Fig. 1). An overall fit factor of $\geq$100 (indicating $\leq$1% leakage into the FFR) was considered a passing score, similar to requirements used by OSHA to pass a standard quantitative fit test [US Department of Labor, 1998]. Fit Plus™ for Windows (TSIMN) software was used for fit test data recording and analysis. The study was carried out in a heating/ventilation/air conditioning (HVAC)-controlled laboratory with daily temperature and relative humidity monitored. To ensure adequate particle counts (the N95 Companion™ requires a minimum of 70 particles/cm^3 to operate) in the laboratory environment, nebulized sodium chloride solution was aerosolized continuously throughout testing.

A FLIR Model SC 5600-M High Resolution Cooled IRC (FLIR Systems, Inc., North Billerica, MA), that operates in the 3–5 μm spectral range and has a temperature measurement accuracy of ±1%, was utilized for thermal imaging throughout the fit testing procedures and InSb Altair software (Altair, Troy, MI) was used for post-processing of thermal images. Based upon the roughly 1.5–2.0°C difference in the exhaled breath and facial perioral skin temperature [Dubrowski, 1975; Jones, 1982; Rustmeyer et al., 2007], post-processing of thermal images was carried out over a similar narrow IRC temperature range (1.5°C) that optimizes detection of very small temperature changes (i.e., the 256 discreet colors or gray levels in the palettes of most IRCs that indicate temperature changes are spread over a much narrower temperature distribution, thereby colorimetrically identifying very small changes in temperature) [Electrophysics Resource Center, 2009]. Thermal imaging was supervised by one of the investigators (WDM), a Level II thermographer certified by the Infrared Training Institute (Billerica, MA). Skin emissivity (the ratio of energy radiated by a particular material to energy radiated by a black body at the same temperature with black body defined as an object that absorbs all radiation energy that impinges on it and, conversely, is a perfect radiator, $\varepsilon = 1$ [Ng et al., 2006]) was set at 0.98, as previously established [Steketee, 1973]. Subjects stood throughout testing and the IRC was positioned directly in front of them for most images (images are generally taken at 90° to the surface because angle changes sometimes cause increased reflectance leading to errors in recorded temperatures [Jones, 1998; Memarian et al., 2009]) at a distance of 1 m (distance affects the accuracy of IRC [Ng et al., 2006]), as has been used in prior breath and facial skin thermal imaging studies [Chekmenev et al., 2005; Ng et al., 2006]. A dark drape hanging against a wall served as the background to minimize reflectivity.

The subjects had their oral temperature taken, were randomly assigned an N95 FFR, donned it and performed negative and positive user seal checks (USC) in accordance with the manufacturer's user instruction [US Department of Labor, 1998] while standing. Any necessary adjustments to the N95 FFR were carried out until the subjects felt a good fit was achieved and could subsequently pass the USC without detecting a face seal leak. Next, subjects wore the N95 FFR for a 3-min acclimatization period, following which the fit test commenced with concurrent continuous recording by the IRC at 60 frames-per-second. Subjects were encouraged to report any subjective sensations of air leakage during the testing and their comments were recorded on a data form. A minimum of a 10-min respite was afforded subjects between each of the modified fit tests, and all testing for any individual subject was carried out consecutively on 1 day. Only IRC data from the normal breathing, deep breathing, and speaking portions of the modified fit test were utilized for analysis of leak detection because movement associated with the other portions of the fit test procedure (e.g., up-and-down movement of the head, etc.) leads to motion artifact that can be associated with spurious temperature measurements [Agostini et al., 2008]. Leaks were identified when a change in skin temperature (that was not associated with movement artifact) was observed during exhalation in the region of the face bordering the N95 FFR (see Fig. 2 for example of exhalation leak with warming effect on facial skin). IRC temperature resolution (the ability to detect small temperature differences) was calculated by subtracting the mean temperature of pixels in the region of interest (peri-mask skin) at baseline from that observed during a leak and averaging the findings over all detected leaks. Differences in fit factors between fit tests conducted when subjects and the IRC-detected leaks and when they did not were analyzed by *t*-tests and confirmed with the nonparametric Wilcoxon two sample test. A contingency table was constructed to analyze any differences in leak detection between groups with passed and failed fit tests (Table II) and was analyzed with Fisher's exact test. A P-value <0.05 was considered statistically significant. Our null hypothesis was that the IRC would not detect leakage on N95 FFR that achieved a passing score on quantitative fit testing.

RESULTS

All subjects completed all fit tests. The laboratory mean temperature and relative humidity during testing were 23.6°C (±2.6°C) and 24.0% (±4.4%), respectively.

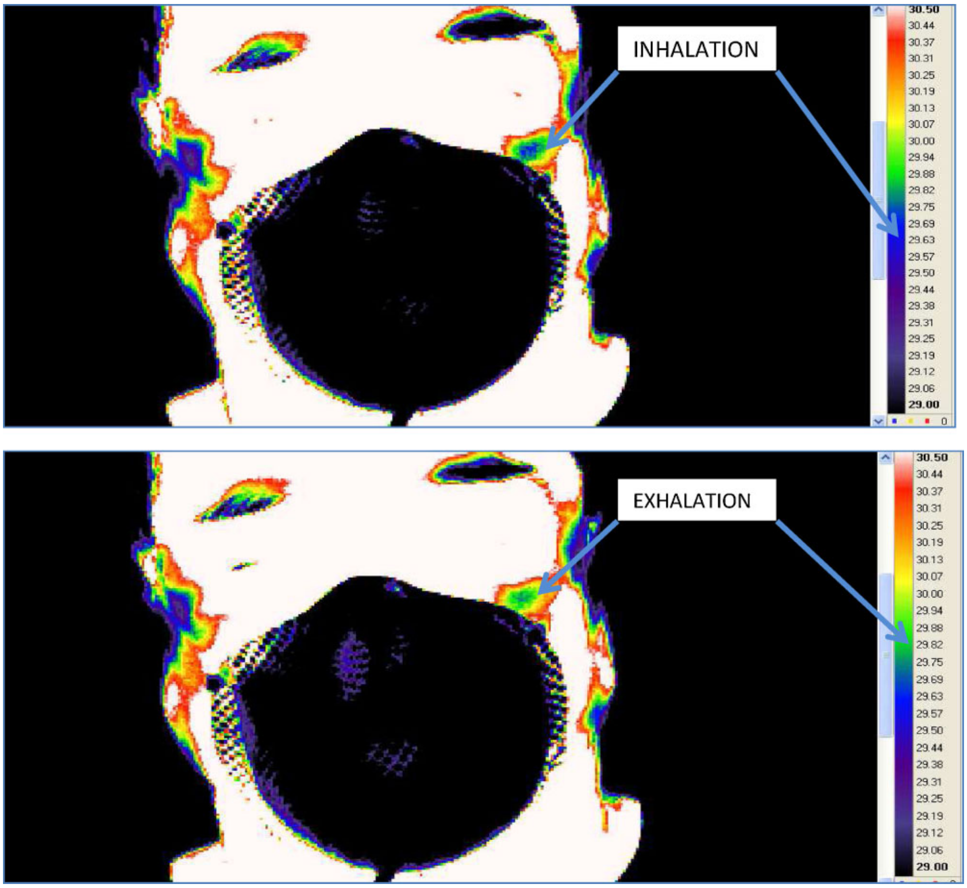

FIGURE 2. Respiratory phase infrared colorimetric facial skin temperature changes of left malar (cheekbone) region leak during a failed respirator quantitative fit test that achieved a fit factor of 94 (1.5°C infrared temperature range; ambient temperature and relative humidity of 22.5°C and 18%, respectively).

TABLE III. N95 Filtering Facepiece Respirator Quantitative Fit Factor Results Using the Portacount Plus® With N95 Companion™

Subject	3M 1860	3M 1860S[a]	Moldex 2200	Moldex 2201[a]	3M 8210	3M 8110S[a]
1	184[b]	84[b]	200	200	68	21[b]
2	200[c]	200	200	200[c]	200	200
3	200	137[b]	200	200	200	200
4	113	200	200[c]	200	200[c]	200[c]
5	74[b]	9[d]	200[c]	200	17	10[d]
6	176	200	65[d]	68	193[b]	200
7	92	200[c]	76	200[c]	200[d]	200[d]
8	200[c,d]	83[d]	94	138[d,b]	200[b]	99[e]
Harmonic mean	134	49	154	124	77	43

[a]Small size respirator.
[b]Reported sensing air leakage.
[c,d]No leak on thermal imaging.
[d]Two leaks on thermal imaging.
[e]Three leaks on thermal imaging.

Mean oral temperature was 36.6°C (±0.19°C) and no subject was febrile. A total of 34/48 quantitative tests (71%) achieved a fit factor ≥100 (Table III). Three subjects (two women, one man) passed 6/6 tests, two subjects (one man, one woman) passed 4/6 tests, two subjects (two men) passed 3/6 tests, and one man passed 2/6 tests. A total of 49 exhalation leaks were detected at 10 anatomic sites [bridge of nose, bilateral sides of nose, bilateral infraorbital regions, bilateral malar (cheekbone) regions, bilateral buccal (cheek) regions and chin area (Fig. 3)] during 39/48 tests (81%). Thirty tests had one IRC-identified exhalation leak, eight had leaks identified at two different anatomic sites, one had leaks at three sites, and nine fit tests had no exhalation leaks observed by IRC (Table III). Subjects reported sensing air leaks on eight separate occasions (six in the nasal area, two along the buccal region) during fit checks or normal breathing and seven (87%) of these were detected by IRC in the anatomic region reported by the subject (three of these were associated with passing scores). There was a significant difference in the incidence of exhalation leaks for failed tests compared to passed tests ($P = 0.04$, Table II). Fit factors were significantly higher for the fit tests (n = 9) without IRC leak detection (200; median 200) compared to fit tests (n = 39) with leaks (67; median 193, $P = 0.01$). However, fit factors were not significantly different ($P = 0.11$) for the fit tests where the subject reported feeling a leak (n = 8, median 110.5) versus when they did not (n = 40, median 200).

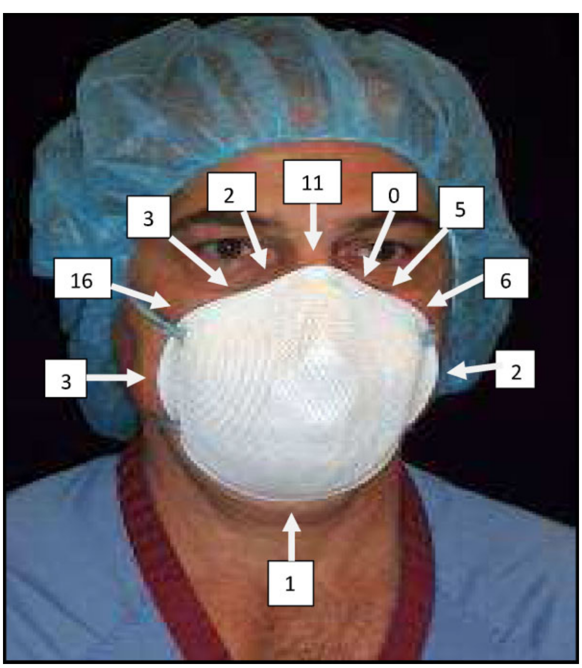

FIGURE 3. Location and number of exhalation leaks detected by infrared camera during quantitative fit testing of N95 filtering facepiece respirators.

Cooling of facial skin occurred with 25 exhalation leaks and warming was associated with 24 leaks. The mean temperature resolution for the IRC was 0.21°C (±0.17) and leaks were noted across the entire spectrum of laboratory temperatures and humidity recorded on test days.

DISCUSSION

The average exhaled breath temperature of healthy men is 34.5°C [Dubrowski, 1975; Jones, 1982], but is subject to variability based on other inputs (e.g., ambient temperature, reactive airways disease, frequency, and depth of breathing, etc.). The average facial skin temperature in the perioral region is variable, but averages 32.5–33.5°C under ambient conditions of 22°C and 50% relative humidity [Rustmeyer et al., 2007]. Thermal image quality and skin temperature measured by IRC is dependent upon such factors as the ambient temperature and humidity, air transmittance, IRC distance, thermal properties of the skin overlying the arterial blood supply in the anatomic region of interest, and skin emissivity [Jones, 1998; Ng et al., 2006; Williams et al., 2008]. In the current study, an IRC was able to identify sites of exhalation air leakage from the FFR/face interface during quantitative fit testing of N95 FFR, with the nasal region and malar regions accounting for 71% of leak sites (Fig. 2). Face seal leak distributions for FFR utilizing an IRC during fit testing have not been previously reported, but the 26.5% incidence for nasal region leaks in the current study compares favorably with the 32.9% and 36.7% incidences reported in two previous studies addressing leaks in subjects wearing elastomeric half-mask respirators [Oestenstad et al., 1990; Oestenstad and Bartolucci, 2010]. The nasal region as a major contributor to FFR leakage is recognized [Health and Safety Executive, 2009] and not surprising given its bony prominence and thin skin covering, as well as the variability of nasal features based on such issues as ethnicity, gender, prior trauma, surgery, etc., coupled with the variability in available FFR features (e.g., pliable nose bars, pre-molded nasal contours, internal flanges, etc.). The bony prominence of the malar (cheekbone) regions and the comparative thinness of the overlying skin also lend themselves to seal problems with FFR.

Leak evaluation with the IRC determined that there was a significant difference ($P = 0.01$) in fit factors associated with leaks compared to those without that was confirmed by the Wilcoxon two sample test. As initially assumed, the harmonic mean fit factors of the wrong size FFR (small size) were lower than those of the appropriate size FFR (Table III). Achieving the maximum 200 fit factor reportable by the PortaCount Plus with N95 Companion® did not ensure the absence of exhalation leaks as identified by the IRC. In fact, exhalation leaks were observed in 19/28 tests (68%) with a fit factor of 200. Conversely, a fit factor of 200 was observed for all nine tests in which no leaks were noted. Despite each subject performing pre-test negative and positive USC [US Department of Labor, 1998] and verbally reporting no air leakage, eight subjects subsequently reported sensing air leakage during actual testing and four of these achieved fit factors of >100 (Table III). As has been pointed out in recent investigations, the USC frequently does not correlate with passing or failing a respirator fit test and may relate to such factors as structural differences in respirator models, variation in donning technique, the size of the wearer's hands as relates to the respirator's external surface area (for cupping the respirator during performance of the USC), facial sizes, and ethnicity-related facial features, subjective differences in the perception of air leakage, etc. [Derrick et al., 2005; Lam et al., 2011]. On the other hand, the finding of no exhalation leaks by IRC in one subject with a fit factor of 200 who had sensations of air leakage on his face suggests that the IRC may be more accurate than subjective perceptions of air leakage and potentially could be employed to further evaluate the efficacy of the USC [Monaghan et al., 2009], but this assumption will require significant additional study.

The ability to achieve a passing score on a fit test (i.e., fit factor ≥100) in the presence of a leak(s) is related to several possibilities including the leak(s) occurring during exhalation only or being of such small caliber that they seal themselves on inspiration due to the negative pressures generated, either of which would not allow for increased particle penetration into the N95 FFR that would lower fit factors. Higher fit factors can also be achieved in the presence of small inward leaks because they are more restrictive to airflow than larger leaks [Lee et al., 2005]. A subject can also have a momentary inhalation leak during an individual fit test exercise, yet still achieve an overall passing score because sampling was done continuously during all of the integrated exercises (resulting in a single count, instead of an individual fit factor for each exercise). The IRC could miss a leak if motion artifact were present, as during other portions of the test associated with greater movement (e.g., side-to-side head turning, etc.). Further, when considering all tests with fit factors of 200, those without IRC-identified leaks may possibly have had significantly higher absolute fit factors than those with leaks inasmuch as the PortaCount® Plus with N95 Companion® limits fit factors to a reportable maximum of 200, irrespective of the actual level attained. In this study, not observing an exhalation leak by IRC in an N95 FFR during quantitative fit testing was associated with a fit factor of 200. This suggests that not viewing a FFR leak on IRC (during normal breathing, deep breathing, or speaking without associated significant head movement) may indicate an initially adequate fit, and further implies that IRC may have a role as a screening tool in determining post-donning respirator fit, though this supposition will require a much larger human study to validate.

Limitations of the current study include the small number of subjects and limited number of fit tests performed. Also, our subjects were all Caucasian and did not offer the variability of facial anatomy based on ethnicity, so our findings on distribution of anatomic leaks cannot be generalized (there are no ethnic effects on skin emissivity, however [Steketee, 1973]). Only three models of N95 FFR were investigated; nevertheless, these models are among the most commonly used in the U.S. N95 FFR with exhalation valves were not tested and the data from the current study may not be applicable to such models. Other respiratory protective devices (e.g., elastomeric air-purifying respirators, gas masks, etc.) were not evaluated in the current study, so that the value of IRC for leak detection in those devices cannot be stated. However, the previously reported use of IRC for evaluation of the thermal stress of a full facepiece, negative pressure respirator [Scanlon and Roberts, 2001] suggests that its use in leak detection of such apparatuses is possible. An IRC identifies only exhalation leaks that, as mentioned, may seal themselves during subsequent inhalation (depending on the size of the leak). However, recent investigation suggests that it is reasonable to assume that exhalation leaks and inhalation leaks occur concurrently in some respiratory protective equipment (RPE) [Oberg and Brosseau, 2008]. This is a rational supposition since an exhalation leak implies a subject (anatomic) and/or FFR (structural) sealing defect that is likely to occur persistently or intermittently during both phases of respiration. However, this is not meant to imply that exhalation and inhalation leaks are necessarily of equal prominence and IRC is not a substitute for inhalation leak testing. Exhalation leaks are also important from the perspective of transmissible diseases if the wearer is infected (either symptomatically or asymptomatically) as this can result in infectious agent dispersal. In the current study, all subjects exhibited exhalation leaks at the same anatomic site for a minimum of two different mask models (mean 3.25 models, ±1.03), thereby highlighting the probable effect of anatomy upon FFR fit. An IRC does not allow for accurate detection of thermal changes associated with leaks during movement, as occurs with various fit test maneuvers (e.g., side-to-side head turning, up-and-down head lifting, etc.) because the kinetics of motion lead to signal fluctuation artifact (noise) that appears as apparent temperature changes due to superimposition of thermal images [Agostini et al., 2008]. Therefore, for accurate detection of leaks, head movement should be minimized, as during the normal breathing, deep breathing, and speaking portions of the fit test procedure. Because of this significant limitation due to movement artifact, it is unlikely that thermal imaging can ever substitute fully for a respirator fit test as currently configured.

Quantitative fit testing serves to assist in estimating the protective function of RPE through analysis of differences in particle counts between the interior (dead space) of the RPE and ambient particulate counts. Although useful, fit factors cannot ascertain the source of the breach in integrity of the RPE (e.g., leakage at face seal site, etc.). The current study, and prior data [Dowdall et al., 2005], demonstrate the potential utility of the IRC in enhancing the evaluation of the protection afforded by RPE by offering a visual representation of leak sites. Further, elevated RPE dead space temperatures are associated with the inability to tolerate RPE wear for extended periods [Baig et al., 2010] and the ability of the IRC to monitor RPE surface temperatures as an indirect indicator of RPE dead space temperatures [Monaghan et al., 2009] may assist researchers investigating this phenomenon. Also, other areas of FFR IRC research could include quantifying the magnitude of temperature change with the achieved fit factor, and IRC's role in the detection of inward leaks. Such information could be useful to researchers, manufacturers, and users. Detection of respirator leaks utilizing IRC requires thermal imaging experience and great attention to detail, as numerous factors (e.g., reflectance, motion artifact, temperature, emissivity, etc.) can alter the quality of the thermal images and result in potentially faulty data. Nonetheless, as IRCs have improved over the years and costs have declined, thermal imaging offers the benefit of relatively inexpensive, non-contact temperature measurement that is of potential utility as a training tool for respirator users and as a possible screening tool for RPE fit. Further, IRC determination of respirator sites that are most prone to leakage (Fig. 3) could assist in the redesign of various features leading to improved respirators that offer more protection (e.g., enhanced retention straps, improved pliable nose bars, evaluation of heat dissipation through various types of exhalation valves, etc.).

CONCLUSIONS

The use of an IRC has enabled the detection of exhalation leaks in N95 FFR during the normal breathing, deep breathing, and speaking segments of quantitative fit testing and allowed for an initial observation of the relative association of various facial anatomic sites with exhalation leaks. Significant additional research is needed to elucidate the ultimate role of IRC in the evaluation of RPE.

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