

Effect of Exhaled Moisture on Breathing Resistance of N95 Filtering Facepiece Respirators

RAYMOND J. ROBERGE^{1*}, EMILY BAYER¹, JEFFREY B. POWELL²,
AITOR COCA¹, MARC R. ROBERGE¹ and STACEY M. BENSON²

¹National Institute for Occupational Safety and Health, National Personal Protective Technology Laboratory, Pittsburgh, PA 15236, USA; ²Technology Research Branch, EG & G Technical Services, Pittsburgh, PA 15236, USA

Received 5 January 2010; in final form 15 April 2010; published online 3 June 2010

This study evaluated the effect of exhaled moisture on the breathing resistance of three classes of filtering facepiece respirators (FFR) following 4 h of continuous wear at a breathing volume of 40 l min⁻¹, utilizing an automated breathing and metabolic simulator as a human surrogate. After 4 h, inhalation and exhalation resistance increased by 0.43 and 0.23 mm of H₂O pressure, respectively, and average moisture retention in the respirators was 0.26 ml. Under ambient conditions similar to those of the current study, and at similar breathing volumes, it is unlikely that exhaled moisture will add significantly to the breathing resistance of filtering facepiece respirators (FFR) over 4 h of use.

Keywords: breathing resistance; filtering facepiece respirators; moisture; N95; respiratory protective equipment

INTRODUCTION

The effect of exhaled moisture upon the breathing resistance of filtering facepiece respirators (FFR) has been mentioned anecdotally (Bailar *et al.*, 2006; Mardimae *et al.*, 2006; Weiss *et al.*, 2007; Hsu and Liu, 2008; Khaw *et al.*, 2008), but scientific data are lacking to either establish or refute this claim. The presumption is that exhaled moisture clogs the voids in the fibrous filtration media (primarily by condensation) thereby increasing the breathing resistance (Belkin, 1996; Mardimae *et al.*, 2006). Because increased breathing resistance at low-to-moderate work rates augments the work of respiration via the additional physiological burden of compensatory mechanisms (e.g. increases in respiratory rate, tidal volume, and heart rate), it would be important to know the extent, if any, of the effect of exhaled moisture on the breathing resistance of FFR. Such basic data would be valuable to FFR stakeholders (e.g. manufacturers, users) in de-

veloping improved moisture-resistant filters and determining appropriate wear times. This study was undertaken to determine any effects of exhaled moisture upon the breathing resistance of FFR.

MATERIALS AND METHODS

National Institute for Occupational Safety and Health (NIOSH)-certified FFR were selected for the current study based upon available information regarding their constituent layers with respect to hydrophobic (moisture repellency) and hydrophilic (moisture attraction) properties (Viscusi *et al.*, 2009). Models selected included class N95 FFR, class N95 FFR with an exhalation valve (N95 FFR/EV), and class surgical N95 FFR (SN95 FFR). SN95 FFR are N95 FFR that are certified by NIOSH as respirators and also cleared by the Food and Drug Administration (FDA) as medical devices, which have been designed and tested and shown to be equivalent to surgical masks in certain performance characteristics (i.e. resistance to blood penetration, and biocompatibility) that are not examined by NIOSH during its certification of N95 FFR (FDA,

*Author to whom correspondence should be addressed.
Tel: +412-386-5241; fax: +412-386-6864;
e-mail: rroberge@cdc.gov

2004). Seven models were cup shaped, one was a duckbill style (Kimberly-Clark 46827), and one was a flat-fold model (3M 1870). Five replicates of three different models from each of the three classes of FFR were tested ($n = 45$) (Table 1).

The inner surface area of FFR (exhaled moisture contact area) was measured by three-dimensional images captured using the 3dMDcranial5™ System (3dMD, Atlanta, GA, USA). The system employs an industrial grade optics approach based on active stereophotogrammetry (the process of making scale drawings from photographs). Five cameras simultaneously capture an object and thereby generate a three-dimensional point cloud of x , y , and z coordinates which can be used for measurement purposes. A representative FFR from each of the nine models studied was selected and five simultaneous images were captured for each FFR with the 3dMDcranial5 System. This procedure was repeated five times for each representative FFR to arrive at a mean inner surface area value that was then imported into Polyworks 10.1.6 software (InnovMetric, Quebec, Canada). The surface of each scan used in the analysis contains a mesh of polygons. By selecting the polygons of interest, various measurements can be performed, including surface area. The FFR inner surface area was determined from the selection of all visible polygons located on the inside of the res-

pirator. N95 FFR/EV were measured for the full inner surface, with and without inclusion of the exhalation valve. The inner surface area of one model of N95 FFR/EV (i.e. 3M 8511) contains a soft cover web/seal along the periphery of its inner layer that was included in its inner surface area calculation because it has the potential for moisture absorption (Table 1). FFR were not preconditioned prior to use, and a new FFR was used for each trial. All five FFR replicates for a given model were from the same package.

An automated breathing and metabolic simulator (ABMS) (Ocenco, Inc., Pleasant Prairie, WI, USA), which consists of a bidirectional artificial lung assembly reproducing sinusoidal breathing patterns of respiratory gases that are heated and humidified to simulate human respiratory metabolism, was used as a human surrogate. The ABMS simulates the metabolic response of a human at any various exercise levels and concurrently performs instantaneous measurements of a complete set of respiratory response variables, including dynamic metabolic simulation of oxygen consumption, carbon dioxide production, water vapor exchange, nitrogen exchange, temperature and humidity for both inspired and expired cycles, breathing characteristics including inhalation and exhalation pressures, ventilation volume, breathing frequency, and breathing waveform shape (Harris and Ashby, 2006). For the current

Table 1. FFR models investigated (modified from Viscusi *et al.*, 2009)

FFR	Outer layer	Middle layer	Inner layer	Inner layer surface area (cm ²)
N95 FFR class				
3M 8210	Hydrophobic	Hydrophobic	Hydrophilic	188.90 (±1.20)
3M 8000	+/-	No middle layer	-/+	179.62 (±1.40)
Moldex 2200 ^a	Hydrophobic	No middle layer	Hydrophobic	211.40 (±2.80)
SN95 FFR class				
Kimberly-Clark 46827	Hydrophobic	Hydrophobic	Hydrophobic	255.20 (±1.72)
3M 1870	Hydrophobic	Hydrophobic	Hydrophobic	217.92 (±1.45)
3M 1860	Hydrophobic	Hydrophobic	Hydrophilic	189.76 (±1.40)
N95 FFR/EV class				
3M 8211	Hydrophobic	Hydrophobic	Hydrophilic	185.68 ^b (±1.69)
				172.64 ^c (±1.57)
3M 8511	Hydrophobic	Hydrophobic	Hydrophilic	175.56 (±0.61)
				158.56 ^c (±0.71)
Moldex 2300 ^a	Hydrophobic	No middle layer	Hydrophobic	217.60 (±1.60)
				202.20 ^c (±0.60)

+/- indicates outer side of layer is hydrophilic and inner side of layer is hydrophobic.

-/+ indicates outer side of layer is hydrophobic and inner side of layer is hydrophilic.

^aRespirator has a mesh plastic support skeleton (nonfiltering) covering the entire outer surface and another between its outer and inner filtering layers.

^bIncludes the surface area of the web/seal on the inner surface.

^cInner surface area minus exhalation valve area.

study, ABMS humidity was set at 100%, the water bath was heated to 41°C, and the trachea warmed to 39°C. Inhalation and exhalation resistances were obtained by an in-line Validyne P305D pressure transmitter (Validyne Engineering Corporation, Northridge, CA, USA) in the ABMS breathing circuit that has a pressure range of ± 22.2 inches H₂O (i.e. 564 mm H₂O) and accuracy of $\pm 0.25\%$ of the full scale (i.e. ± 1.41 mm H₂O) (Tam and Ghajar, 1997). The pressure transmitter was calibrated to a water manometer. Laboratory environmental conditions over the 3-month study period averaged: temperature 20.40°C (range, 18.10–21.50°C), relative humidity 51.76% (range, 40.00–63.50%), and barometric pressure 736.95 mmHg (range, 727.90–742.30 mmHg). ABMS measurements are reported as standard temperature and pressure, dry.

One-inch wide (25.4 mm) waterproof adhesive tape (Johnson & Johnson, Skillman, NJ, USA) was placed along the entire periphery of tested FFR, which were then weighed on a precision Accu 6201 electronic scale (Fisher Scientific, Hampton, NH, USA). FFR were affixed to a Sheffield breathing mannequin headform (INSPEC International Ltd, Greater Manchester, UK) that was attached to the ABMS. The FFR tethering bands were applied as per the manufacturers' instructions [i.e. lower band at the rear of the neck, upper band across the occiput (crown) of the head] and the FFR were further secured to the mannequin's face utilizing the previously applied tape. The ABMS was programmed to deliver heated humidified air for 4 h continuously at 40 l min⁻¹ (respiratory rate 24, tidal volume 1.670 ml) corresponding to the upper level of a moderate work rate (Caretti *et al.*, 2004) that is used for NIOSH respirator certification testing (Szaladja, 2008). The 4-h test period was selected because it seemed reasonable to assume that during a regular 8-h work shift, it could be expected that no more than four continuous hours of wear would occur when one factors in breaks in the work schedule (e.g. meal time, and bathroom breaks). Pressure measurements were recorded as 1-min averages continuously over a 4-h period. The mean inhalation and exhalation pressures recorded for the first five minutes of each FFR test served as controls. Throughout testing, a FLIR Model 6300 thermal imaging camera (FLIR Systems, Wilsonville, OR, USA) monitored for the presence of FFR leaks, as previously described (Monaghan *et al.*, 2009). Identified leaks were sealed with additional adhesive tape and subsequent thermal imaging verified elimination of the leak. At the end of the experiment, FFR were immediately reweighed (minus any additional

tape used to seal identified leaks) to estimate moisture retention.

Statistical analysis

Inhalation and exhalation resistances (measured as mm H₂O pressure) and weight change data (measured in grams) are reported as means (standard deviation). The time of the sessions was 4 h and all variables are summarized at control and at the end of 4-h sessions (pre- and post-trial). To assess differences between the N95 FFR, SN95 FFR, and N95 FFR/EV in moisture retention during 4 h of exercise, a 3 × 2 (FFR type × pre/post weight) analysis of variance (ANOVA) was performed. To determine differences for individual models within each FFR class, a one-way ANOVA for inhalation resistance, exhalation resistance, and weight changes from control to the end of the 4-h period was performed using the values of the five trials that were tested for each model with Bonferroni corrections and the α -level set at $P < 0.05$. The null hypothesis was that there would be no significant differences ($P > 0.05$) in the studied variables between N95 FFR, SN95 FFR, and N95 FFR/EV. SPSS version 17.0 software (SPSS, Inc., Chicago, IL, USA) was used for statistical analysis.

RESULTS

Moisture retention

The mean temperature of exhaled air during the study was 33.88°C, correlating closely with the level (34°C) cited for humans (Winslow *et al.*, 1942). There was a significant difference ($P = 0.01$) between the mean control weight of FFR that persisted (but did not change statistically) after 4 h of use (Table 2). There was no significant difference in the control weight of N95 FFR compared to SN95 FFR ($P = 0.72$), but N95 FFR/EV weighed significantly more than N95 FFR ($P = 0.01$) and SN95 FFR ($P = 0.007$). The 4-h FFR mean moisture retention was 0.26 gm (range, 0.00–1.00 gm) and did not differ significantly between the three classes ($P = 0.10$) (Table 2). However, there were 4-h significant increases in weight among individual models of class N95 FFR ($P = 0.01$) and class N95 FFR/EV ($P = 0.006$) but not among class SN95 FFR ($P = 0.98$). In order to compensate for the differences in surface area between the various models of FFR and the presence of an exhalation valve on the amount of functional FFR surface area, we standardized average moisture gain over 4 h 100 cm⁻² of FFR filter area [SN95 FFR (0.16 ± 0.03 gm); N95

Table 2. Mean breathing resistance values and moisture retention.

Respirator class	Control inhalation resistance (mm H ₂ O)	4-h inhalation resistance (mm H ₂ O)	Control exhalation resistance (mm H ₂ O)	4-h exhalation resistance (mm H ₂ O)	Control weight (gm)	4-h weight (gm)	4-h weight gain (gm)
N95 FFR	-13.80 (±1.59)	-14.09 (±1.90)	7.37 (±2.02)	7.24 (±2.10)	13.15 (±3.76)	13.34 (±3.85)	0.19 (±0.10)
SN95 FFR	-14.45 (±0.70)	-15.09 (±0.67)	7.47 (±0.41)	8.06 (±0.38)	12.35 (±0.69)	12.70 (±0.69)	0.35 (±0.01)
N95 FFR/EV	-14.09 (±1.02)	-14.43 (±1.10)	6.41 (±1.22)	6.66 (±1.19)	20.80 (±2.43)	21.03 (±2.36)	0.23 (±0.09)
Mean	-14.11 (±1.05)	-14.54 (±1.23)	7.08 (±1.30)	7.32 (±1.37)	15.43 (±4.63)	15.69 (±4.62)	0.26 (±0.10)
Between group <i>p</i> -value	0.79	0.66	0.61	0.51	0.01	0.01	0.10

FFR (0.09 ± 0.05 gm); N95 FFR/EV (0.13 ± 0.06 gm)] and noted no significant differences versus controls ($P = 0.33$). There also were no significant differences between FFR classes in moisture retention 100 cm⁻² of filter surface area [SN95 FFR versus N95 FFR ($P = 0.15$); SN95 FFR versus N95 FFR/EV ($P = 0.48$); N95 FFR versus N95 FFR/EV ($P = 0.41$)].

Inhalation resistance

The mean inhalation resistance for controls of -14.11 mm (±1.05) was not significantly different among the three classes of FFR ($P = 0.79$) (Table 2). Head-to-head comparisons of FFR classes also revealed no significant differences in inhalation resistance among controls [N95 FFR versus SN95 FFR ($P = 0.51$); N95 FFR versus N95 FFR/EV ($P = 0.76$); SN95 FFR versus N95 FFR/EV ($P = 0.71$)].

After 4 h of use, the mean inhalation resistance increased to -14.54 mm (±1.23) (range, -11.0 to -17.9 mm) and did not differ significantly between FFR classes ($P = 0.66$) (Table 2). The mean increase in inhalation resistance of -0.43 mm (±0.39) also was not significantly different between the three classes of FFR ($P = 0.55$). Head-to-head comparisons of FFR classes after 4 h did not reveal any significant differences [N95 FFR versus SN95 FFR ($P = 0.38$); N95 FFR versus N95 FFR/EV ($P = 0.76$); SN95 FFR versus N95 FFR/EV ($P = 0.56$)]. Also, no significant differences were noted in 4-h inhalation resistance changes among the individual models of class N95 FFR ($P = 0.09$), class SN95 FFR ($P = 0.87$), and class N95 FFR/EV ($P = 0.47$).

Exhalation resistance

The mean exhalation resistance for controls was 7.08 mm (±1.30) (range, 3.5–15.3 mm) and was not significantly different among the three classes of FFR ($P = 0.61$). Head-to-head comparisons of FFR classes likewise demonstrated no significant differences in exhalation resistance for controls [N95 FFR versus SN95 FFR ($P = 0.93$); N95 FFR versus N95 FFR/EV ($P = 0.42$); SN95 FFR versus N95 FFR/EV ($P = 0.38$)] (Table 2).

After 4 h, the mean exhalation resistance increased to 7.32 mm (±1.37) and did not differ significantly between FFR classes ($P = 0.51$). The 4-h mean change in exhalation resistance was 0.24 mm (±0.36) and differed significantly between the three classes of FFR ($P = 0.02$). Head-to-head comparisons of FFR classes after 4 h demonstrated no difference between SN95 FFR compared with N95

FFR/EV ($P = 0.11$), but a significantly lower exhalation resistance for N95 FFR compared with SN95 FFR ($P = 0.007$) and some trending toward significant differences for N95 FFR/EV compared to N95 FFR ($P = 0.07$). Within the three FFR classes, there were no significant differences in 4-h exhalation resistance changes among the individual models of SN95 FFR ($P = 0.99$) and N95 FFR/EV ($P = 0.47$), but some trending toward significance between models of N95 FFR ($P = 0.07$).

DISCUSSION

The high moisture content and high temperature of the exhaled breath can cause moisture to condense in FFR due to temperature differences between ambient air and that in the FFR dead space (Li *et al.*, 2006). The amount of moisture retained within an FFR is impacted by the breathing volume, ambient temperature and humidity, water retention properties of the FFR (i.e. hydrophobic, hydrophilic), amount of surface area of the FFR [dependent upon the style (e.g. duckbill, flat fold, pleated, and cup shaped) and size (e.g. small, medium, large) of the FFR] and the presence of an exhalation valve (for models so equipped). Water droplets, by virtue of their high surface energy, exhibit a high contact angle (beading) when they come in contact with low surface energy hydrophobic surfaces, such as polypropylene (the major constituent of most modern FFR filters). The beading theoretically may be responsible for blocking the filtration media pores. By contrast, the dioctylphthalate (DOP) oil used in NIOSH FFR certification testing has low surface energy characteristics and tends to coat polypropylene fibers and not block FFR pores, thereby not impacting breathing resistance (at the 200 mg DOP loading level used for certification testing) (Martin and Moyer, 2000).

Our study showed FFR mean moisture retention of 0.26 gm (i.e. 0.26 ml of H_2O) with moderate breathing over a 4-h period. Generally, at sedentary breathing volumes, the amount of moisture in each exhaled breath [exhaled breath condensate (EBC)] averages 100 ul min^{-1} (range, 40–300 ul min^{-1}) (Horvath *et al.*, 2005). However, the EBC is impacted by tidal volume and minute volume (Liu and Thomas, 2007), with a reported EBC of 15.10 ul at a minute volume of 22.50 l (McCafferty *et al.*, 2004). If we apply this EBC data (McCafferty *et al.*, 2004) to the current study (correcting for the 44% greater minute volume of the ABMS), the total potential exhaled moisture from the ABMS over a 4-h period would be 124,992 μl or $\sim 125 \text{ ml}$ [21.70 $\mu\text{l}/\text{breath}$ (corrected)

$\times 24 \text{ breaths min}^{-1} \times 240 \text{ min}$). In such a scenario, the FFR moisture retention noted in the current study (0.26 ml) would represent a mere $\sim 0.02\%$ of the total potential moisture exhaled over 4 h by the ABMS ($\sim 125 \text{ ml}$). Our data are somewhat congruent with a recent study of healthcare workers (wearing N95 FFRs and N95 FFR/EV models used in the current study) that reported mean moisture retention of 0.11 gm over 1 h of treadmill testing at low work rates (Roberge *et al.*, 2010). Interestingly, in the current study, N95 FFR retained less moisture (0.19 mg) than N95 FFR/EV (0.23 gm), a finding also recently noted (Roberge *et al.*, 2010), despite the fact that one of the presumed benefits of exhalation valves is decreased moisture buildup. At low-to-moderate work rates, the exhalation valve of FFR may not be fully activated and the (presumed) benefit of increased moisture expulsion may not be realized (Roberge *et al.*, 2010). The loss of surface area by the presence of a nonfunctional valve ($\sim 8\%$ decrease in surface area for valved FFR in the current study) could be a factor in the lack of any significant difference observed between valved and nonvalved FFR. However, when we standardized water moisture retention by grams per square centimeter, there were no differences noted between FFR with and without exhalation valves. At low-to-moderate work rates, the exhalation valve of FFR may not be fully activated and the (presumed) benefit of increased moisture expulsion may not be realized (Roberge *et al.*, 2010). The loss of surface area by the presence of a nonfunctional valve ($\sim 8\%$ decrease in surface area for N95 FFR/EV in the current study) theoretically could be a factor in the lack of any significant difference observed between valved and nonvalved FFR. However, when we eliminated the exhalation valve area by standardizing moisture retention to grams per square centimeter of filter surface area, there were again no significant differences noted between N95 FFR and N96 FFR/EV ($P = 0.41$).

The current study findings demonstrate a slight (3%), but statistically significant, increase of 0.24 mm (± 0.36) in exhalation resistance ($P = 0.02$) and a nonsignificant 3% increase in inhalation resistance of -0.43 mm (± 0.39) for FFR ($P = 0.66$) after 4 h of use at a moderate breathing volume (40 l min^{-1}). Given the relatively low particulate counts in our laboratory setting, this increased resistance is attributable to moisture retention. The paradoxical mean decrease in exhalation resistance noted for class N95 FFR stands in contrast to the other findings of the study. This may represent the accuracy limitations ($\pm 0.25\%$) of the pressure measurement

apparatus for such a small decrease (-0.13 mm) in pressure, or the development of small leaks at the FFR periphery that were not identified on thermal imaging and allowed air escape with a subsequent decrease in exhalation pressure. The mean increases of 3% in exhalation and inhalation resistances over 4 h, in low-resistance respirators such as N95 FFR, would likely be imperceptible to the wearer. In ambient conditions similar to those of the current study, and at similar breathing volumes, it is unlikely that exhaled moisture will add significantly to the breathing resistance of N95 FFR, SN95 FFR, and N95 FFR/EV over 4 h of use.

Limitations of the current study include the fact that it is a nonhuman study and the ABMS does not reproduce the innate human variability in breathing patterns. However, the ABMS does allow for controlled studies and offers excellent reproducibility of conditions. The study duration was 4 h, rather than a standard 8-h work shift. However, as previously mentioned, 4 h seemed more plausible as a maximum that an FFR would be worn without the need for removal (break periods and meals). It is possible that more water retention and an added impact on breathing resistances could occur with use over an 8-h period. The amount of water vapor present on saturated air depends on the air temperature and some data suggest that exhaled breath temperatures may be $1\text{--}2^{\circ}\text{C}$ higher in healthy adults than the mean temperature (33.88°C) of the current study (Paredi *et al.*, 2002). Each 1°C rise in temperature increases water vapor pressure $6\text{--}7.5\%$ (Wentz and Schabel, 2000) so that the absolute increase in expelled moisture (and resultant retained moisture in the FFR) at the higher temperature would be increased proportionally. Breathing resistance determinations for NIOSH FFR certification are carried out at a continuous flow rate of 85 l min^{-1} , rather than the 40 l min^{-1} intermittent breathing volume used in the current study. Nevertheless, the intermittent breathing pattern utilized in the study more closely reflects actual human breathing and the 40 l min^{-1} breathing volume equates with a moderate workload. Testing was not carried out at extremes of temperature and humidity that might have influenced FFR moisture retention to variable degree. It is also possible that our results might have differed had we preconditioned the FFR prior to testing as is required in NIOSH FFR certification (i.e. 85% relative humidity and 38°C temperature for 24 h) that addresses the issue of the impact of humidity on the filter's effectiveness (National Institute for Occupational Safety and Health, National Personal Protective Technology

Laboratory, 2005). High temperature and humidity may compromise respirator function (e.g. increased moisture retention and breathing resistance), but we only tested FFR within a narrow range of nonextreme temperatures and relative humidity in a controlled laboratory setting. We only tested nine different models of FFR and can therefore not comment on other models. Moisture retention is, in part, dependent upon the composition of the fiber material. All FFR in the current study were of polypropylene composition because this is the most common component of modern low-resistance FFR and is highly hydrophobic. It is likely that FFR utilizing other fibers would display different moisture retention properties. The variability of performance among FFR, even those of the same model, noted in this study argues for more investigation. Distilled water that was used for study humidification differs somewhat from moisture expelled from the respiratory tract that contains various constituents (e.g. electrolytes, nitrite, and protein) (McCarthy *et al.*, 2004; Effros *et al.*, 2002). However, this should have had minimal impact because water comprises 99% of exhaled moisture (Horvath *et al.*, 2005). Lastly, because of the issue of retained moisture within the circuitry of the ABMS that would not have been easily measured, we relied on calculations of the amount of moisture potentially expelled from the ABMS through the FFR rather than measuring the actual volume of water in the ABMS before and after each experiment. However, this would only impact calculation of the percentage of retained moisture, not the actual moisture content as determined from the FFR weight calculations before and after each FFR trial.

CONCLUSIONS

Moisture exhaled over 4 h from an ABMS through a breathing mannequin fitted with NIOSH-certified N95 FFR, SN95 FFR, and N95 FFR/EV, at a moderate breathing volume and mean ambient conditions of 20.40°C temperature (range, $18.10\text{--}21.50^{\circ}\text{C}$) and relative humidity 51.76% (range, 40.00–63.5%), did not accumulate to any significant degree within the FFR. A minor increase (3%) in inhalation and exhalation resistances occurred concurrently that would likely be imperceptible to the wearer. Exhaled moisture does not significantly impact the mechanics of breathing resistance while wearing N95 FFR, SN95 FFR, and N95 FFR/EV over 4 h at moderate breathing volumes.

FUNDING

Internal National Institute for Occupational Safety and Health internal operating funds.

Acknowledgements—The authors thank National Personal Protective Technology Laboratory colleagues Drs Ronald Shaffer and Nina Turner, Jay Snyder, and William Newcomb for their reviews of the manuscript and helpful suggestions.

Disclaimers—The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the NIOSH.

REFERENCES

- Bailar JC, Brosseau LM, Cohen HJ *et al.* (2006) Reusability of facemasks during an influenza pandemic. Washington, DC: Institute of Medicine, National Academies Press.
- Belkin NL. (1996) A century after their introduction, are surgical masks necessary? (Opinion). *Assoc Oper Room Nurses J*; 64: 602–7.
- Caretti DM, Gardner PD, Coyne KM. (2004) Workplace breathing rates: defining anticipated values and ranges for respirator certification testing Report ECBC-TR-316. Aberdeen, MD Edgewood Chemical and Biological Center, U.S. Army Research, Development and Engineering Command.
- Effros RM, Hoagland KW, Bosbous M *et al.* (2002) Dilution of respiratory solutes in exhaled condensates. *Am J Respir Crit Care Med*; 165: 663–9.
- FDA. (2004) Guidance for industry and FDA staff: surgical masks—pre-market notification [501 (k)] submissions; guidance for industry and FDA. Available at <http://www.fda.gov/MedicalDevices/DeviceRegulationandGuidance/GuidanceDocuments/ucm072549.htm>. Accessed 11 April 2010.
- Harris RJ, Ashby JW. (2006) Effects of long-term temperature extremes on self-contained self-rescuers: initial findings. Report to the Director of the Office of Miners' Health, Safety and Training. Charleston, WV: West Virginia Office of Miners.
- Horvath I, Hunt J, Baranes PJ. (2005) Exhaled breath condensate: methodological recommendations and unresolved questions. *Eur Respir J*; 26: 523–48.
- Hsu W-H, Liu W-C. (2008) Assessment of physiological loads and subjective discomforts for wearing N95 facemask. (Abstract) International Conference of Healthcare Systems, Ergonomics and Patient Safety. Strasbourg, FR, June 25–27, 2008. Available at <http://www.heps2008.org/abstract/data/POSTER/Hsu.pdf>. Accessed 28 May 2009.
- Khaw KS, Kee WDN, Tam YH *et al.* (2008) Survey and evaluation of modified oxygen delivery devices used for suspected severe acute respiratory syndrome and other high-risk patients in Hong Kong. *Hong Kong Med J*; 14: 27–31.
- Li Y, Wong T, Chung J *et al.* (2006) In vivo protective performance of N95 respirator and surgical facemask. *Am J Ind Med*; 49: 1056–65.
- Liu J, Thomas PS. (2007) Relationship between exhaled breath condensate volume and measurements of lung volumes. *Respiration*; 74: 142–5.
- Mardimae A, Slessarev M, Han J *et al.* (2006) Modified N95 mask delivers high inspired oxygen concentrations while effectively filtering aerosolized microparticles. *Ann Emerg Med*; 48: 391–9.
- Martin SB, Jr, Moyer ES. (2000) Electrostatic respirator filter media: filter efficiency and most penetrating particle size effects. *Appl Occup Environ Hyg*; 15: 609–17.
- McCafferty JB, Bradshaw TA, Tate S *et al.* (2004) Effects of breathing pattern and inspired air conditions on breath condensate volume, pH, nitrite, and protein concentrations. *Thorax*; 59: 694–8.
- Monaghan WM, Roberge MR, Rengasamy M *et al.* (2009) Thermal imaging comparison of maximum surface temperatures achieved on N95 filtering facepiece respirators with and without exhalation valves at sedentary breathing volumes. *J Intl Soc Resp Protect*; 26: 12–9.
- National Institute for Occupational Safety and Health, National Personal Protective Technology Laboratory. (2005) Determination of particulate filter penetration to test against solid particulates for negative pressure, air-purifying respirators: standard testing procedure. Procedure No. RCT-APR-STP-0057, 0058, 0059. Available at <http://www.cdc.gov/niosh/npptl/stps/pdfs/RCT-APR-0057%2058%2059.pdf>. Accessed 13 April 2010.
- Paredi P, Kharitonov SA, Barnes PJ. (2002) Faster rise of exhaled breath temperature in asthma. *Am J Respir Crit Care Med*; 165: 181–4.
- Roberge RJ, Coca A, Williams WJ *et al.* (2010) Physiological impact of filtering facepiece respirators (“N95 Masks”) use on healthcare workers. *Respir Care*; 55: 569–77.
- Szaladja J. (2008) Powered air-purifying respirator (PAPR) concept paper. Pittsburgh, PA: National Personal Protective Technology Laboratory. Available at <http://www.cdc.gov/niosh/npptl/resources/pressrel/letters/pdfs/ltr010308.pdf>. Accessed 2 November 2009.
- Tam L-M, Ghajar AJ. (1997) Effect of inlet geometry and heating on the fully developed friction factor in the transition region of a horizontal tube. *Exp Ther Fluid Sci*; 15: 52–64.
- Viscusi D, Bergman M, Eimer B *et al.* (2009) Evaluation of five decontamination methods for filtering facepiece respirators. *Ann Occup Hyg*; 53: 815–27.
- Weiss MM, Weiss PD, Weiss DE *et al.* (2007) Disrupting the transmission of influenza A: face masks and ultraviolet light as control measures. *Am J Pub Health*; 97: S32–7.
- Wentz FJ, Schabel M. (2000) Precise climate monitoring using complementary satellite data. (Letter). *Nature*; 403: 414–6.
- Winslow C-E A, Herrington LP, Nelbach JH. (1942) The influence of atmospheric temperature and humidity upon the dryness of the oral mucosa. *Am J Hyg*; 35: 27–39.