

Thermal Imaging Comparison of Maximum Surface Temperatures Achieved on N95 Filtering Facepiece Respirators with and without Exhalation Valves at Sedentary Breathing Volumes

William D. Monaghan, Marc R. Roberge, Manivel Rengasamy
and Raymond J. Roberge

Centers for Disease Control, National Institute for Occupational Safety and Health,
National Personal Protective Technology Laboratory, 626 Cochran's Mill Road,
Pittsburgh, PA 15236

Corresponding Author E-Mail: RRoberge@cdc.gov

ABSTRACT

One of the purported benefits of exhalation valves on filtering facepiece respirators is increased wearer comfort through enhanced elimination of exhaled breath-associated heat to the environment, but published data attesting to the efficacy of these valves to accomplish this action is scant. This breathing mannequin-based study utilized infrared camera technology to examine the maximum surface temperature attained in two models of N95 filtering facepiece respirators with exhalation valves compared to two similar respirators without exhalation valves. No significant differences were noted when comparing respirators without valves to respirators with valves from the same manufacturer; however, respirators with valves, as a group, tended to exhibit a greater maximal surface temperature than respirators without valves ($p=0.05$). At sedentary breathing volumes of one hour duration, N95 filtering facepiece respirators with exhalation valves may offer no benefit in heat dissipation over that of similar filtering facepiece respirators without exhalation valves.

Keywords: filtering facepiece respirators, exhalation valves, surface temperatures, infrared camera imaging

INTRODUCTION

Comfort is a major determinant of compliance with filtering facepiece respirator (FFR) use (Goldfrank and Liverman, 2007). An individual's determination of comfort while wearing a FFR is a composite of various inputs, including breathing rate and volume, breathing resistance, CO₂ retention, O₂ decrements, thermal sensations, communication ease, and psychological issues, to name but some of these variables (Roberge, 2007; Guo et al, 2008). Increased facial warmth beneath a FFR is uncomfortable for the wearer, is one of the most common reasons for non-compliance with use, and has been suggested as a potential trigger for claustrophobic/anxiety reactions (Laird et al 2002). Facial thermal stress significantly increases the subjective perception of breathing difficulty and discomfort (Li et al, 2005).

To help cope with this associated thermal stress, some FFR models are available with exhalation valves that are designed to reduce facial warmth by decreasing resistance to the egress of exhaled air and its related heat (Kuo et al, 2005). However, some FFR users work at sedentary rates and may not generate levels of exhaled heat comparable to workers at higher energy outputs. Published data addressing heat dispersal in FFR with valves versus FFR without valves are few in number. One recent study (Guo et al, 2008) comparing a FFR with dual exhalation and dual inhalation valves to a FFR with dual exhalation valves (that also served as inhalation valves), noted a lower FFR surface temperature of the former (derived from cheek temperatures). Prior studies examining respirator-associated increases in facial heat have relied upon temperature probes placed on the facial skin beneath FFRs (Li et al, 2005; Guo et al, 2008); however, this method provides a measurement of the temperature only in the immediate locale of the probe. Thermal imaging with infrared (IR) cameras allows qualitative and quantitative temperature determinations over wide surface areas or smaller, focused regions. Thermography uses the IR spectral band of the electromagnetic spectrum, involving four bands: near IR (0.75 μ m), middle IR (3 -6 μ m), far IR (6 – 15 μ m), and extreme infrared (15 – 100 μ m)); IR cameras collect thermal radiation emitted from surfaces, but do not themselves emit energy (Chekmenev et al, 2005). Thermal imaging has previously been utilized in studies of other respirator-related issues (e.g., fit testing, thermal stress) (Dowdall et al, 2005; Scanlon and Roberts, 2001), but there is little data available on the use of thermal imaging for evaluating temperature gradients across FFR. The use of IR imaging for measuring breathing-related parameters is based upon the fact that the temperature of exhaled air is higher than that of the background of the typical indoor environment (Murthy and Pavlidis, 2006). The current study was undertaken to compare the maximum surface temperature achieved by N95 FFRs with valves (N95 FFRs/EV) and N95 FFRs without valves (N95 FFRs) during the end-exhalation phase of respiration at sedentary breathing volumes associated with adult males.

MATERIALS AND METHODS

A Sheffield breathing mannequin headform (INSPEC International Ltd., Greater Manchester, UK), Attached to an Automated Breathing and Metabolic Simulator (ABMS) (Ocenco, Inc., Pleasant Prairie, WI), served as a human surrogate for testing purposes. The ABMS, used since the 1980's by NIOSH for testing of respiratory protective equipment, consists of a bi-directional artificial lung assembly in which respiratory gases are heated and humidified to simulate human respiratory metabolism (Harris and Ashby, 2006). The ABMS was programmed to deliver 100% humidity and 33° C tracheal air at a breathing volume of 10L/min (breathing rate of 14, tidal volume of 714 mL), based on published breathing volume data for sedentary average-sized adult males (California Environmental Protection Agency, 1994). Room temperature was maintained at 22° C and relative humidity at 55% - 60% during testing.

Four replicates each of two (medium/large) N95 FFR models (Moldex 2200, 3M 8210) and two similar N95FFR/EV models (Moldex 2300, 3M 8511) were individually tested by adhering them to the mannequin headform utilizing PoliGrip® (Smith/Kline/Glaxo, London, UK), a commercial dental adhesive. Individual FFRs were tested from the same lot for each model in order to minimize lot-to-lot variability and were not pre-conditioned prior to testing. Each respirator was tested over a one-hour period.

An IR camera (Agema 550 camera, FLIR USA, North Billerica, MA) was used to monitor and quantify the surface temperature of the N95FFRs. The IR camera utilized in this study detects IR radiation, in wavelengths ranging from 3.6 μ m - 5 μ m (middle IR band), and measures temperatures to an accuracy of ± 2 °C or $\pm 2\%$ of the temperature range. Mounted on a tripod, the IR camera was positioned at approximately one meter from the mannequin headform for improved optics (Chekmenev et al, 2005). With an upper limit on temperature measurement of 33° C (i.e., the ABMS tracheal air temperature setting), the emissivity of the respirator (i.e., the ability of a surface to emit radiant energy compared to that of a black body at the same temperature and with the same area) was set at 0.84. The IR camera measured surface temperatures of the N95FFR and the surrounding temperatures in an approximately

0.09 m² (0.28 m x 0.32 m) rectangular area around the N95FFR. Pixel counts utilized to determine respirator surface temperatures averaged 12,769 per N95FFR. Manual focusing of the IR camera was utilized to optimize the resolution quality (1.6 mm) of the thermal images. Thermal images were obtained at 30-second intervals during the one-hour test period for each respirator (total of 120 thermal images per N95FFR tested). Maximum temperatures reached on the surface of each FFR (including the exhalation valve, when so equipped), representing the end-exhalation air coming from the lung parenchyma (Paredi et al, 2003), were recorded (Figure 1), and standard deviations were calculated for each respirator model. ThermoCam Research 2001 software (FLIR systems, Burlington, ON, Canada) was used to record temperature data. Post-processing of the temperature data was carried out with Microsoft Excel® (Microsoft, Redmond, WA).

Statistical Analysis – A paired t-test was used for comparison of the means of the end-exhalation maximum surface temperatures of the two models of N95 FFR/EV and their counterpart N95FFR models, as well as for grouped comparisons of all valved N95 FFRs/EV compared with all N95 FFRs. For this study, a $p < 0.05$ was considered statistically significant.



Figure 1. Infrared camera image of N95 filtering facepiece respirator during end exhalation.

RESULTS

The maximum (end-exhalation) temperatures attained on the surface of the N95 FFR Moldex model 2200 and its counterpart N95 FFR/EV Moldex model 2300 averaged 29.69° C (SD $\pm$ 0.80) and 30.61° C (SD $\pm$ 0.07), respectively ($p=0.12$). The mean maximum temperatures attained on the surface of the N95 FFR 3M model 8210 and its counterpart N95 FFR/EV 3M model 8511 averaged 28.47° C (SD $\pm$ 1.05) and 30.26° C (SD $\pm$ 1.84), respectively ($p=0.20$) (Table I). There was no significant difference between the maximum temperatures attained on the surface of the N95 FFR Moldex 2200 (29.69° C [SD $\pm$ 0.80]) compared with the N95 FFR 3M 8210 (28.47° C [SD $\pm$ 1.05]) ($p=0.14$), or for the N95 FFR/EV Moldex 2300 (30.61° C [SD $\pm$ 0.07]) and the N95 FFR/EV 3M 8210 (30.26° C [SD $\pm$ 1.84]) ($p=0.69$). The higher maximum surface temperatures recorded for the composite group of all eight N95 FFRs/EV (30.44° C [SD $\pm$ 1.24]) compared to all eight N95 FFRs (29.08° C [SD $\pm$ 1.08]) bordered on statistical significance ($p=0.05$).

Table I. Mean Maximum End-Exhalation Surface Temperatures of N95 Filtering Facepiece Respirators at Sedentary Breathing Volumes

N95 filtering facepiece respirator model	Mean maximum end-exhalation temperature (°C)	p-value
Moldex 2200	29.69 (SD $\pm$ 0.80)	0.12
Moldex 2300*	30.61 (SD $\pm$ 0.07)	
3M 8210	28.47 (SD $\pm$ 1.05)	0.20
3M 8511*	30.26 (SD $\pm$ 1.84)	

* exhalation valve model

DISCUSSION

Our thermal imaging measurements of emitted energy (heat) in the current study demonstrate that, at breathing volumes associated with sedentary activity in an average-sized adult man (California Environmental Protection Agency, 1994) over a one hour period, there is no significant difference in the mean maximum end-exhalation temperatures achieved on the surface of N95 FFRs/EV when compared with similar N95 FFRs from the same manufacturer. However, grouped comparisons of the N95 FFRs with N95 FFRs/EV (each group composed of both manufacturers' models [N = 8]) indicated that latter achieved higher maximum surface temperatures that bordered on statistical significance ($p=0.05$).

These findings, though somewhat counter-intuitive because it was expected that N95 FFRs/EV would permit the egress of greater amounts of heat (Hyashi and Tokura, 2004) by lowering air resistance during exhalation (Kuo et al, 2005), are congruent with the fact that no gross movement of exhalation valves was observed during ABMS testing in this study, signifying that the exhalation valves were not activated at these sedentary breathing volumes. Further, the N95 FFR/EV valve cover temperature was noted to be much lower than that of the respirator surface, suggesting no tracheal air movement across the valve (Figure 2). Recent human studies addressing the issue of FFR-associated temperature have demonstrated findings similar to our data, lending support to our results. Hayashi and Tokura (2004) compared valved and non-valved FFR models and demonstrated respirator microclimate temperatures of $\pm 29^{\circ}$ C at sedentary activity. Another study, utilizing computational fluid dynamics to ascertain the effect of a FFR on temperature fields around the mouth, demonstrated temperatures of 30° C in association with the inner surface of the FFR and 29° C with the outer surface (Kasahara et al, 2004). Li et al (2005) noted surface temperatures of $\pm 27^{\circ}$ C at a mild work rate (3.2 km/hr [2 mph]) for a non-valved N95FFR model that was also used in the current study (3M 8210). The combination of a low pressure respirator (i.e., N95 FFR) and sedentary breathing volumes may not allow for generation of the streamlined air flows

developed during exhalation in respirators with exhalation valves that are thought to enhance exhaled air egress to the ambient atmosphere (Saatci et al, 2004). Hypothetically, it may also be possible that the N95 FFR/EV area covered by a non-activated exhalation valve functionally results in a decrease in that respirator's surface area available for exhalation and associated heat transfer. Higher thermal readings in the respirator surface area immediately in contact with the exhalation valve (as observed in the current study) may indicate that the valve is not participating in heat transfer equivalent to other areas of the respirator surface. (Figure 2)

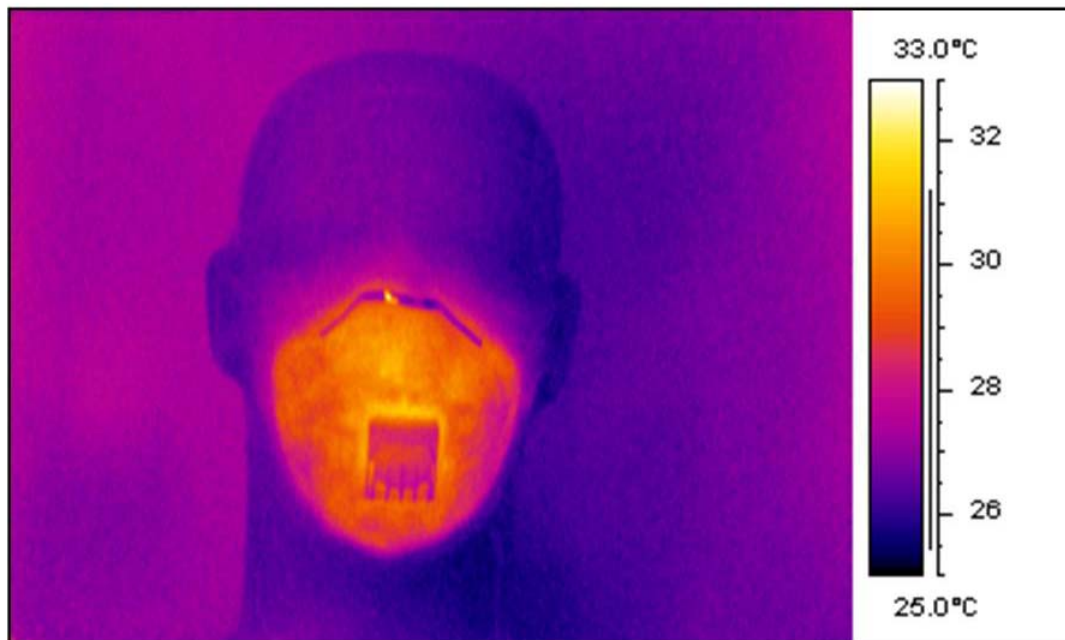


Figure 2. Infrared camera image of N95 filtering facepiece respirator equipped with an exhalation valve.

Limitations of the current study include the small sample size (i.e., 16 respirators tested from four N95 FFR models of two manufacturers) and the fact that it was a mannequin study that did not account for the breathing variability inherent in human subjects. Breathing volumes utilized were of a sedentary adult male (California Environmental Protection Agency, 1994) and would not reflect breathing patterns and heat exchange expected in work settings associated with physical exertion. However, there are also many work situations in which N95 FFR are worn in relatively sedentary conditions (e.g., clerical staff in potentially infected hospital environs, dental assistant, etc.). We did not sample from the inhalation phase of respiration and exhalation phases other than end-exhalation. Although sampling from all phases of the respiratory cycle would provide overall mean surface temperatures of N95 FFRs during the one hour time period, the end-exhalation phase offers the worst-case scenario in that it does not include the cooling contribution of admixed ambient air (22° C in this study) that normally occurs during the inhalation phase of respiration. The four different respirator models used in this study have differing surface areas and thicknesses, factors that would influence heat dissipation and distribution. Imprecise emissivity estimations can affect temperature quantification; however, inasmuch as most non-metallic objects have emissivities >0.8, slight variations in the selected emissivity at these levels lead to only minor changes in the surface temperature determinations (Mollman et al, 2005). Respirator leakage, due to poor adhesion to the mannequin/headform, could have allowed for loss of some heat; however, the IR camera easily

detects leaks (Dowdall et al, 2005) (Figure 3) and none were noted during the current study. Lastly, we only tested two models each of N95 FFRs and N95 FFRs/EV, so that our data may not be applicable to other N95 FFR models.

The potential ramifications of this study are that the use of N95 FFRs/EV at sedentary work rates over one hour periods, for purposes of comfort related to dispersal of metabolic-related heat to the ambient environment, may not be warranted for N95 FFR wearers and the additional cost of these models may not be justified. Our finding of higher mean surface temperatures attained in N95 FFRs/EV is important in light of the fact that higher surface temperatures on FFR may correlate with higher respirator microclimate temperatures (Guo et al, 2008). Respirator microclimate temperatures $>34.5^{\circ}\text{C}$ have been associated with decreased respirator wear (Laird et al, 2002). Our preliminary findings will need to be validated in human trials before the issue of heat dispersal from N95 FFRs/EV versus N95 FFRs at sedentary work rates can be fully analyzed. Future IR investigations should also attempt to elucidate any correlation of respirator temperature with underlying facial skin temperature. IR technology may ultimately prove useful for investigating a variety of issues related to respirator protective equipment (e.g., leakage determinations, heat buildup, fit test correlations, user seal check analysis in real time, etc.).

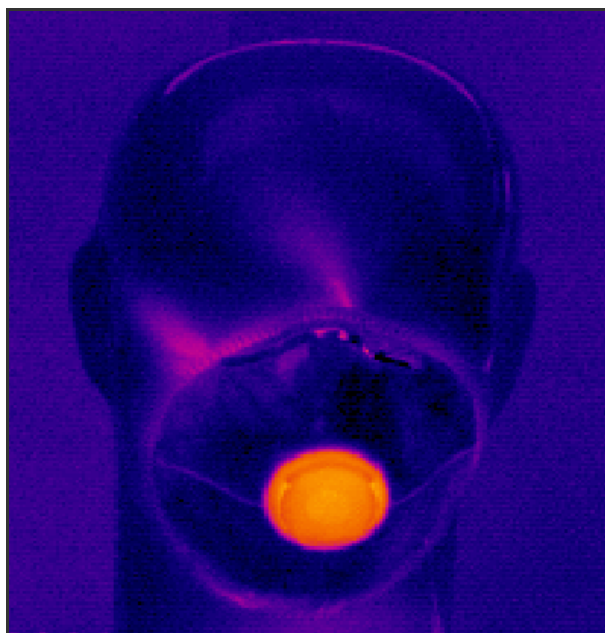


Figure 3. Infrared camera image demonstrating leakage at the mannequin/filtering facepiece respirator interface.

CONCLUSIONS

At breathing volumes for a sedentary adult male over a one hour period, N95 FFRs/EV offered no advantage over N95 FFRs in the dissipation of respirator surface heat as determined by IR camera measurements. As a group, N95 FFRs/EV were associated with higher mean maximum surface temperatures than comparable models of N95 FFRs ($p=0.05$). The use of N95 FFRs/EV, for purposes of heat dissipation, may not be necessary at sedentary breathing volumes over a one hour period, but human studies will be needed to confirm our study findings. IR technology offers potential utility in evaluating this issue and a number of other issues associated with respiratory protective equipment use.

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