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Powered air-purifying respirator use in healthcare: Effects on thermal sensations and comfort

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ABSTRACT

Twelve subjects wore an N95 filtering facepiece respirator (N95 FFR), one tight-fitting full facepiece powered air-purifying respirator (PAPR), two loose-fitting PAPRs, and one elastomeric/PAPR hybrid for 1 hr each during treadmill walking at 5.6 km/hr while undergoing physiological and subjective response monitoring. No significant interaction ($p \geq .05$) was noted between the five respirators in heart rate, respiratory rate, oxygen saturation, transcutaneous carbon dioxide, and perceptions of breathing effort or discomfort, exertion, facial heat, and overall body heat. Respirator deadspace heat/humidity were significantly greater for the N95 FFR, whereas tympanic forehead skin temperatures were significantly greater for the hybrid PAPR. Temperature of the facial skin covered by the respirator was equivalent for the N95 FFR and hybrid PAPR, and both were significantly higher than for the other three PAPRs. Perception of eye dryness was significantly greater for a tight-fitting full facepiece PAPR than the N95 FFR and hybrid PAPR. At a low-moderate work rate over 1 hr, effects on cardiopulmonary variables, breathing perceptions, and facial and overall body heat perceptions did not differ significantly between the four PAPRs and a N95 FFR, but the tight-fitting, full facepiece PAPR increased perceptions of eye dryness. The two loose-fitting PAPRs and the full facepiece tight-fitting PAPR ameliorated exercise-induced increases in facial temperature, but this did not translate to improved perception of facial heat and overall body heat.

KEYWORDS
Physiological effects; respirators; subjective perceptions; thermal effects

Introduction

The role of personal protective equipment (PPE), including respiratory protective equipment, has received much attention over the past decade in response to outbreaks of prominent infectious pathogens (Middle East Respiratory Syndrome, pandemic influenza, Ebola, etc.) associated with significant morbidity and mortality to both patients and healthcare workers. PPE use, especially partially or fully encapsulating ensembles, often creates an inverse relationship between protection and comfort; that is, the higher the level of protection, the greater the negative impact on comfort. This is an important issue given that comfort can influence both PPE use compliance and duration of work cycles.[1,2] An oft-cited contributor to respiratory protective equipment-related discomfort is the perception of increased warmth, either regional (i.e., facial area) or global.[1] Recently, much interest has been directed towards the role of powered air-purifying respirators (PAPRs) in healthcare settings during infectious disease outbreaks, based upon multiple advantageous features,[3] including possible amelioration of some heat-related issues via cooling effects of PAPR air currents.[4,5] Respiratory protective equipment-related heat perceptions are plausibly attributable to associated increases in either core temperature (rectal, brain, tympanic) or the temperature of the skin covered by the respirator. Research studies addressing physiological responses to N95 filtering facepiece respirators (N95 FFR), at sedentary and low-moderate work rates in temperate ambient environments over 1–2 hr, have reported no significant effects on core (intestinal, rectal) temperatures[1,6] or on indirect measurements of brain temperature.[7] The temperature of the facial skin under an N95 FFR rises above baseline values and regularly reaches the level at which facial heat sensory receptors are activated and transmit afferent impulses to the brain,[7,8] thereby suggesting that this is the site of origination of respiratory protective equipment-associated heat perceptions. Thus, actions that serve to decrease the temperature of facial skin covered by this equipment may decrease thermal sensations

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and, secondarily, improve comfort and tolerance. Unfortunately, there is a dearth of research data with respect to the impact of PAPRs on the user. The current study was undertaken to determine any physiological effects and subjective perceptions of PAPRs that impact measures of thermal sensation and comfort. This information may be beneficial to workers who utilize respiratory protective equipment, respiratory protection program managers, and researchers.

Materials and methods

Twelve heathy, non-smoking subjects (6 men, 6 women) were recruited for the study from a pool of experienced research subjects who had previously participated in various studies on respiratory protective devices and thermal effects of protective clothing ensembles at our laboratory. Anthropometrics for the men were age 23 ± 3 years (yr), height 180.3 ± 8.2 centimeters (cm), weight 78.8 ± 6.3 kilograms (kg), Body Mass Index (BMI) 24.3 ± 2.1 kg/meter^2 (m^2); values for women were age 23 ± 3 yr, height 168.2 ± 6.0 cm, weight 68.3 ± 9.5 kg, and BMI 24.1 ± 2.8 kg/m^2. All study subjects were evaluated by a licensed physician prior to study participation (including pregnancy testing for women) and study trials were carried out in a National Institute for Occupational Safety and Health (NIOSH) research laboratory with mean temperature of 20–22°C and 40–50% relative humidity during testing. The study was approved by the NIOSH Institutional Review Board and all subjects provided oral and written consent prior to study participation.

Subjects were attired in a one-piece 65% polyester/35% cotton coverall (Williamson-Dickie Mfg. Co., Fort Worth, TX), socks and athletic shoes, and sat for a 20-min stabilization period prior to exercise trials. Following stabilization, subjects wore each of four randomly assigned models of PAPRs and one model of an N95 FFR for 1-hr each while on a treadmill at 5.6 km/hr and 0° incline, a work rate that is comparable with healthcare work (see Table 1 and Figure 1).[9] There was a minimum respite of 30 min between trials, and subjects completed no more than two trials in any given day.

Instrumentation included a Zephyr BioHarness chest strap (Zephyr Technology Corp., Annapolis, MD) for continuous monitoring of heart rate (HR) and respiratory rate (RR), and a heated, ear-mounted Tosca sensor (Radiometer, Brea, CA) that provided continuous pulse-derived oxygen saturation (SpO_2) and transcutaneous carbon dioxide ($tcPCO_2$) levels. Tympanic temperature was recorded at 0, 20, 40, and 60 min with a Thermoscan® 4000 infrared aural thermometer (Braun, Melsugen, Germany). Facial skin temperature was measured at the upper lip region of the cheek area

Table 1. Respirators evaluated in the current study.

Respirator	Style	Head covering	Airflow during testing	Weight
3M 1870+	N95 filtering facepiece respirator	N/A	N/A	0.011 kg (0.02 lb)
Koken BL321S	Tight-fitting breath response hybrid elastomeric/PAPR*	Loose-fitting shroud (cellulose based resin) not contiguous with PAPR	Tidal volume on inhalation only	PAPR 0.18 kg (0.40 lb); battery and battery pack 0.185 kg (0.41 lb)
MSA OptimAir TL	Tight-fitting PAPR	Advantage 4000 silicone full-face mask with nasal cup	115 LPM	PAPR 1.860 kg (4.1 lb); face mask 0.726 kg (1.6 lb)
MaxAir DLC CAPR 36	Loose-fitting PAPR	Helmet and loose-fitting shroud (polypropylene) with High Efficiency cuff (polyethylene)	190 LPM	2.631 kg (5.8 lb)
3M Versaflo	Loose-fitting PAPR	BE -10 loose-fitting hood and shroud (polycoated Tyvek)	185 LPM	1.941 kg (4.28 lb)

*PAPR = powered air-purifying respirator

Figure 1. Respirators evaluated in the current study (Photo credit: CDC/NIOSH/NPPTL).

immediately above the left labial commissure and at the mid-forehead region with wireless combination temperature and humidity sensors (IButton, Dallas, TX) affixed with a hypoallergenic, transparent, water-resistant perforated plastic tape (Transpore, 3M Co., St. Paul, MN). The respirators' microclimate (temperature and humidity) was similarly evaluated with an IButton sensor affixed to the inner surface of the respirator immediately lateral to the right labial commissure area. A 9-point thermal sensation scale[10] (ranges from very cold [−4] to neutral [0] to very hot [+4]), that is an extended version of the 7-point American society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) scale found in the ASHRAE Standard 55–1992 on thermal comfort and is used worldwide,[11] was used to quantify subjective impressions of overall body temperature and facial temperature. A 4-point thermal comfort scale[12] ("comfortable", "slightly uncomfortable", "uncomfortable", "very uncomfortable") developed by Zhang[13] was used to measure body temperature-associated comfort. Perception of breathing effort was evaluated with a 7-point scale that ranges from "not noticeable" (+1) to "intolerable" (+7), and breathing discomfort was quantified with a 7-point scale ranging from "no discomfort" (+1) to "intolerable discomfort" (+7), both of which have been previously utilized in other respiratory protective device studies.[14,15] The perception of exertion was quantified with the Borg Rating of Perceived Exertion (RPE),[16] a 15-point score that ranges from "very, very light" (7) to "maximal exertion" that has been shown to be a valid and reliable psychometric tool.[17] Eye dryness was assessed with 7-point scale that ranges from "very dry" (−3) to neutral (0) to "very wet" (+3). All subjective scales were recorded at 0, 20, 40, and 60 min intervals.

Statistical analysis

Dependent variables were analyzed by a mixed-design ANOVA for five different types of respirators over five time points (baseline [no respirator], 0, 20, 40, and 60 min). When a significant interaction was found with Greehouse-Geisser correction for sphericity, post-hoc multiple comparison testing was carried out to identify the observed mean difference between the respirator conditions. Statistical significance was accepted when $p < 0.05$; all analyses were performed using a statistical software package (SPSS v.19, IBM, Somers, NY).

Results

Mean values (±Standard Deviation) for study variables are presented in Tables 2 and 3, and graphic representation of statistically significant variables are found in Figure 2. No statistically significant differences were found for SpO_2 ($F = 2.065$, $p = .098$), $tcPCO_2$ ($F = 2.065$, $p = .098$), HR ($F = .419$, $p = .877$), RR ($F = .955$, $p = .481$), overall body heat perception ($F = .387$, $p = .894$), facial heat perception ($F = 2.065$, $p = .063$), breathing effort ($F = 1.275$, $p = .274$), breathing discomfort ($F = 1.558$, $p = .160$), and RPE ($F = .156$, $p = .981$). Temperature values showed a significant statistical interaction for tympanic temperature ($F = 12.352$, $p < .001$; post-hoc test: Koken > 1870+ [$p < .001$], OptimAir [p <. 001], Maxair [$p = .026$], Versaflo [p.047]), facial temperature ($F = 18.239$, $p < .001$; post-hoc test: Koken = 1870+ > OptimAir [$p < .001$], Maxair [$p < .001$], Versaflo [$p < .001$]), and forehead temperature ($F = 14.483$, $p < .001$; post-hoc test: Koken >1870+ [$p = .037$], OptimAir [$p < .001$], Maxair [$p = .004$], Versaflow [$p = .001$]. The respirator microclimate data analysis indicated a significant statistical interaction for microclimate temperature ($F = 16.301$, $p < .001$; post-hoc test: 1870 > Koken [$p < .001$], OptimAir [$p < .001$], Maxair [$p < .001$], Versaflo [$p < .001$] and Koken > OptimAir [$p = .008$], Maxair [$p = .006$], Versaflo [$p = .001$]) and for microclimate humidity ($F = 6.740$, $p < .001$; post-hoc test: 1870 > Koken [$p = .003$], OptimAir [$p < .001$], Maxair [$p < .001$], Versaflo [$p < .001$] and Koken > Optimair [$p < .001$], Maxair [$p = .015$], Versaflo [$p < .001$]). Eye dryness data indicated a statistically significant difference with the tight-fitting, full facepiece PAPR ($F = 3.107$, $p = .038$; post-hoc test: OptimAir > 1870+ [$p = .020$], Koken [$p = .025$]).

Discussion

The current study data indicate that, at a low-moderate work rate over 1 hr, there is no statistically significant difference between the tested N95 FFR and the four PAPRs in their impact upon measured cardiopulmonary variables (SpO_2, $tcPCO_2$, HR, RR). This likely relates to the fact that these parameters are more impacted by the work rate rather than the respirators,[14] the low breathing resistance of modern N95 FFRs due to the incorporation of electrostatic charging of the filter media allowing for a thinner more breathable respirator,[18] and the ease of breathing associated with air supplied from a PAPR negating the need to overcome filter resistance. These findings are further corroborated by the lack of statistically significant difference among respirator models for perceptions of breathing effort, breathing discomfort and RPE in the current study. It is interesting to note that the additional weight of the loose-fitting and tight-fitting, full facepiece PAPR (2–2.5 kg) (Figure 1) did not demonstrate any significant impact on cardiopulmonary variables given that added weight carriage on the body results in additional energy requirements. Walking while carrying roughly twice this carriage load (5.4 kg) in a backpack has been shown to result in an increased oxygen consumption of only 1.5% VO2max.[19]

Thermal assessment of respirator deadspace (microclimate) heat and humidity levels indicated that the 1870+ values were statistically significantly greater than the Koken that was, itself, greater than values for all other tested respirators (Table 2). This finding reflects the fact that the loose-fitting and full-facepiece PAPR supply of continuous circulating air and the Koken's supply of intermittent air to the respirator deadspace (microclimate) aid in local convective cooling and evaporative effects. The facial temperature data for the Koken and 1870+ were equivalent and both were higher than for the other tested respirators, a finding consistent with the cooling effects of circulating air supplied by the loose-fitting and full-facepiece PAPRs. Although the Koken might be expected to perform better than the 1870+, based upon the assumption that its supplied powered circulating air on inhalation would have some cooling effect on facial skin, the combination molded plastic and silicone body may not dissipate warm exhaled air to the same degree as the porous surface of the 1870+ FFR. The finding that forehead temperature was lower with the loose-fitting and full-facepiece PAPRs relates to the fact that those respirators circulate freshly supplied air to the forehead region, whereas the 1870+ and Koken do not. The Koken was associated with the highest tympanic membrane temperature recordings, a finding that is attributable to its shroud not being contiguous with the respirator, so that no respirator-derived air currents circulate within its confines. The present findings are supported by prior research showing that, at work rates equivalent to the present study, N95 FFR have minimal impact on

Table 2. Mean (±Standard Deviation) values for measured physiological variables (temperatures in °C).

Variable	Respirator	Baseline	0 min	20 min	40 min	60 min
SpO_2	1870+	98.9 ± 0.7	99.1 ± 0.7	98.7 ± 0.8	98.8 ± 0.6	98.8 ± 0.7
	Koken	98.9 ± 0.9	99.0 ± 1.0	98.3 ± 0.8	98.3 ± 0.8	98.3 ± 0.8
	OptimAir	98.7 ± 0.9	98.8 ± 1.0	99.0 ± 0.7	98.8 ± 0.7	98.8 ± 0.6
	Maxair	98.7 ± 0.8	98.8 ± 0.8	98.6 ± 0.9	99.0 ± 0.7	98.6 ± 1.0
	Versaflow	98.6 ± 0.8	99.0 ± 0.9	98.6 ± 0.8	98.4 ± 0.7	98.4 ± 0.9
$tcpCO_2$	1870+	36.8 ± 2.0	37.5 ± 2.4	38.4 ± 2.2	38.2 ± 2.3	38.0 ± 1.9
	Koken	37.4 ± 2.9	37.9 ± 2.8	39.4 ± 3.5	38.8 ± 3.4	38.9 ± 3.6
	OptimAir	37.0 ± 3.0	37.5 ± 3.1	38.0 ± 3.4	37.9 ± 3.1	37.5 ± 2.8
	Maxair	36.8 ± 2.8	36.8 ± 2.4	37.4 ± 2.5	37.2 ± 2.3	37.1 ± 2.3
	Versaflow	37.5 ± 3.1	37.8 ± 3.5	38.8 ± 3.3	38.3 ± 3.1	38.4 ± 3.2
Heart rate	1870+	69.2 ± 7.8	80.7 ± 5.8	110.8 ± 13.1	112.5 ± 14.0	113.8 ± 13.3
	Koken	69.2 ± 7.0	76.4 ± 8.1	108.8 ± 11.0	110.5 ± 13.2	113.9 ± 12.1
	OptimAir	71.8 ± 6.8	80.5 ± 9.9	109.4 ± 10.9	111.3 ± 10.8	110.6 ± 13.1
	Maxair	67.2 ± 6.7	77.3 ± 6.8	104.8 ± 7.0	108.8 ± 7.4	108.5 ± 8.9
	Versaflow	70.6 ± 6.5	78.3 ± 7.0	107.4 ± 7.7	110.9 ± 8.7	111.8 ± 9.4
Respiratory rate	1870+	15.3 ± 3.5	16.7 ± 2.9	26.1 ± 3.5	26.1 ± 3.6	25.8 ± 3.2
	Koken	14.7 ± 3.5	16.2 ± 3.0	23.0 ± 3.4	23.5 ± 4.0	24.6 ± 3.0
	OptimAir	15.1 ± 3.9	16.8 ± 3.5	22.5 ± 5.4	25.2 ± 4.9	25.0 ± 4.2
	Maxair	14.1 ± 3.2	18.5 ± 3.6	25.5 ± 4.3	25.2 ± 4.3	25.7 ± 4.2
	Versaflow	15.0 ± 2.5	17.5 ± 3.0	23.3 ± 4.8	25.1 ± 4.8	28.8 ± 4.3
Tympanic temperature	1870+	36.34 ± 0.37	36.36 ± 0.35	36.59 ± 0.35	36.67 ± 0.40	36.73 ± 0.38
	Koken	36.38 ± 0.34	36.38 ± 0.35	37.14 ± 0.31	37.27 ± 0.35	37.33 ± 0.33
	OptimAir	36.56 ± 0.31	36.56 ± 0.31	36.75 ± 0.27	36.73 ± 0.33	36.75 ± 0.38
	Maxair	36.61 ± 0.23	36.61 ± 0.23	36.71 ± 0.29	36.74 ± 0.38	36.78 ± 0.35
	Versaflow	36.60 ± 0.36	36.60 ± 0.36	36.63 ± 0.33	36.73 ± 0.23	36.72 ± 0.25
Facial temperature	1870+	32.99 ± 0.82	33.44 ± 0.95	34.58 ± 1.19	34.52 ± 1.65	34.61 ± 1.55
	Koken	33.02 ± 1.59	33.53 ± 1.07	34.10 ± 1.00	34.21 ± 0.91	34.28 ± 1.06
	OptimAir	33.09 ± 1.00	32.32 ± 1.19	31.20 ± 0.64	31.32 ± 1.02	31.39 ± 0.97
	Maxair	32.56 ± 0.90	32.19 ± 0.94	30.35 ± 1.03	30.25 ± 1.10	30.28 ± 1.18
	Versaflow	32.88 ± 0.71	32.53 ± 0.99	31.95 ± 1.05	31.99 ± 1.08	32.34 ± 0.99
Forehead temperature	1870+	31.92 ± 0.67	32.04 ± 0.58	31.44 ± 1.29	31.28 ± 1.13	31.20 ± 1.14
	Koken	31.25 ± 1.95	32.13 ± 0.80	32.83 ± 0.83	32.79 ± 0.78	32.88 ± 0.86
	OptimAir	31.54 ± 0.75	31.05 ± 1.08	29.53 ± 0.87	29.13 ± 0.96	29.13 ± 1.00
	Maxair	32.34 ± 1.18	32.24 ± 1.53	29.91 ± 1.41	29.61 ± 1.17	29.52 ± 1.08
	Versaflow	32.25 ± 1.06	31.88 ± 1.13	30.60 ± 1.35	30.58 ± 1.52	30.89 ± 1.30
Microclimate temperature	1870+	26.49 ± 2.11	28.70 ± 1.69	33.61 ± 0.77	33.77 ± 0.81	33.82 ± 0.75
	Koken	24.16 ± 2.14	25.45 ± 1.76	28.28 ± 1.66	28.41 ± 1.32	28.78 ± 1.34
	OptimAir	23.53 ± 1.17	24.78 ± 1.23	26.32 ± 1.10	26.20 ± 1.02	26.20 ± 0.87
	Maxair	24.76 ± 1.44	24.76 ± 1.18	24.19 ± 0.61	24.69 ± 0.73	25.04 ± 0.53
	Versaflow	24.45 ± 2.93	24.45 ± 2.89	25.70 ± 2.52	25.78 ± 2.41	26.36 ± 2.47
Microclimate humidity	1870+	41.3 ± 6.9	66.4 ± 8.5	88.4 ± 8.1	92.8 ± 7.2	94.1 ± 8.1
	Koken	40.1 ± 6.3	64.6 ± 14.7	72.4 ± 11.1	74.0 ± 10.4	75.6 ± 11.6
	OptimAir	39.1 ± 5.1	42.8 ± 5.8	49.7 ± 13.0	62.4 ± 23.0	63.2 ± 24.2
	Maxair	40.9 ± 4.7	43.2 ± 3.9	48.9 ± 3.5	52.5 ± 4.9	54.0 ± 4.2
	Versaflow	43.3 ± 10.8	49.6 ± 8.7	61.3 ± 16.7	60.3 ± 16.7	66.8 ± 16.5

Table 3. Mean values (±Standard Deviation) for subjective perceptions measured in the study.

Variable	Respirator	Baseline	0 min	20 min	40 min	60 min
Overall body heat perception	1870+	− 0.2 ± 0.7	0.0 ± 0.7	1.1 ± 0.8	1.3 ± 0.8	1.4 ± 0.8
	Koken	− 0.4 ± 0.7	− 0.3 ± 0.8	0.8 ± 0.7	1.4 ± 0.5	1.7 ± 0.8
	OptimAir	− 0.3 ± 0.8	− 0.3 ± 0.8	0.7 ± 0.7	1.2 ± 0.7	1.3 ± 0.7
	Maxair	− 0.3 ± 0.8	− 0.3 ± 0.8	0.6 ± 0.5	1.3 ± 0.6	1.3 ± 0.6
	Versaflow	− 0.3 ± 0.9	− 0.3 ± 0.9	0.9 ± 0.7	1.2 ± 0.7	1.4 ± 0.8
Facial heat perception	1870+	− 0.2 ± 0.6	− 0.2 ± 0.6	1.4 ± 0.7	1.7 ± 0.8	1.8 ± 0.8
	Koken	− 0.2 ± 0.7	− 0.2 ± 0.7	1.5 ± 0.7	1.9 ± 0.7	2.3 ± 0.6
	OptimAir	− 0.2 ± 0.7	− 0.2 ± 0.7	0.9 ± 0.8	1.3 ± 0.9	1.3 ± 0.7
	Maxair	− 0.2 ± 0.7	− 0.2 ± 0.7	0.5 ± 0.5	1.0 ± 0.6	1.1 ± 0.5
	Versaflow	− 0.1 ± 0.8	− 0.1 ± 0.8	1.3 ± 0.7	1.5 ± 0.5	1.8 ± 0.8
Breathing effort	1870+	1.0 ± 0.0	1.0 ± 0.0	1.8 ± 0.8	2.0 ± 1.0	1.9 ± 0.8
	Koken	1.0 ± 0.0	1.0 ± 0.0	1.7 ± 0.5	2.0 ± 0.7	1.9 ± 0.7
	OptimAir	1.0 ± 0.0	10 ± 0.0	1.4 ± 0.5	1.7 ± 0.5	1.6 ± 0.5
	Maxair	1.0 ± 0.0	1.0 ± 0.0	1.3 ± 0.5	1.5 ± 0.5	1.5 ± 0.5
	Versaflow	1.0 ± 0.0	1.0 ± 0.0	1.8 ± 0.6	1.8 ± 0.6	1.8 ± 0.6
Breathing comfort	1870+	1.0 ± 0.0	1.0 ± 0.0	1.6 ± 0.9	1.7 ± 0.8	1.6 ± 0.8
	Koken	1.0 ± 0.0	1.0 ± 0.0	1.4 ± 0.8	1.6 ± 0.8	1.6 ± 0.8
	OptimAir	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0	1.1 ± 0.3	1.2 ± 0.4
	Maxair	1.0 ± 0.0	1.0 ± 0.0	1.2 ± 0.4	1.2 ± 0.4	1.2 ± 0.4
	Versaflow	1.0 ± 0.0	1.0 ± 0.0	1.3 ± 0.5	1.4 ± 0.5	1.4 ± 0.5
Rating of perceived exertion	1870+	6.1 ± 0.3	6.1 ± 0.3	9.3 ± 1.9	9.8 ± 1.6	10.2 ± 2.0
	Koken	6.1 ± 0.3	6.1 ± 0.3	9.3 ± 1.8	9.8 ± 2.1	10.1 ± 2.0
	OptimAir	6.1 ± 0.3	6.1 ± 0.3	9.2 ± 1.7	9.7 ± 1.7	10.1 ± 1.8
	Maxair	6.1 ± 0.3	6.1 ± 0.3	8.8 ± 1.5	9.4 ± 1.5	9.9 ± 1.7
	Versaflow	6.1 ± 0.3	6.1 ± 0.3	9.3 ± 2.1	10.0 ± 1.9	10.1 ± 1.8
Perception of eye dryness	1870+	0.3 ± 0.6	0.3 ± 0.6	0.3 ± 0.7	0.3 ± 0.7	0.3 ± 0.6
	Koken	0.3 ± 0.6	0.3 ± 0.6	0.3 ± 0.6	0.3 ± 0.6	0.3 ± 0.7
	OptimAir	0.2 ± 0.6	0.2 ± 0.6	− 0.2 ± 0.9	− 0.4 ± 1.1	− 0.5 ± 1.2
	Maxair	0.2 ± 0.7	0.2 ± 0.7	0.1 ± 0.8	− 0.1 ± 0.8	− 0.1 ± 0.8
	Versaflow	0.2 ± 0.6	0.2 ± 0.6	0.0 ± 0.7	0.1 ± 0.7	0.0 ± 0.7

tympanic temperatures,[20] and that tight-fitting full facepiece PAPRs likewise have no statistically significant effect on core (intestinal) temperatures.[21] Comparative data on the effect of loose-fitting PAPR wear on tympanic membrane temperatures are not readily available. There was a statistically significant finding of greater eye dryness with the OptimAir compared to both the 1870+ and Koken. The OptimAir's constant airflow into its tight-fitting, full facepiece directs air upwards towards the conjunctiva of the eyes, whereas the loose-fitting PAPRs air source flows downward and therefore less directly to the eyes.

As previously mentioned, subjective testing indicated no statistically significant respirator interaction on breathing effort, breathing comfort or RPE. Although there was no statistically significant interaction noted for facial heat perception, some effect of cooling on facial skin is suggested by this parameter's trending toward significance ($p = .063$). Greater subject numbers might have resulted in this parameter reaching statistical significance, although this is speculative. The lack of any statistically significant interaction on the perception of overall body heat likely relates to the fact that, in the temperate environment of the study laboratory, the subjects' baseline body temperature was not elevated so that the respirator-entrained temperate ambient air had little impact on facial heat perception. Also, the relatively short period of physical activity and the low-moderate work rate may not have been sufficient to induce significant heat perceptions. The perception of thermal comfort is the state of mind which expresses satisfaction with the thermal environment,[22] a psychological concept that relies on the desired physiological state (uncomfortable through comfortable), whereas thermal sensation correlates best with skin temperature.[23] The low intersubject variability noted for some of the test variables (i.e., Breathing Effort, Breathing Comfort, Borg RPE) represents the fact that all tested individuals were experienced study subjects who were very physically fit lifelong non-smokers being exercised at a low-moderate workrate in a temperate environment. Thus, it was not surprising that some data would have minimal variability.

Limitations of the current study include the relatively low number of subjects ($n = 12$) and the fact that testing was carried out over only 1 hr. Fit testing was not performed on the N95 FFR nor the tight-fitting PAPR that could have affected results. However, the N95 FFR model tested (3 M 1870+) is advertised as a "one size fits most" unit and has demonstrated a high pass rate on respirator quantitative fit testing.[24] The possibility exists that, under the conditions of the study and limited subject numbers, a small proportion of individuals who might be sensitive to thermal stress at higher work rates or elevated ambient conditions might not be identified. The data in the present study therefore apply to the use of

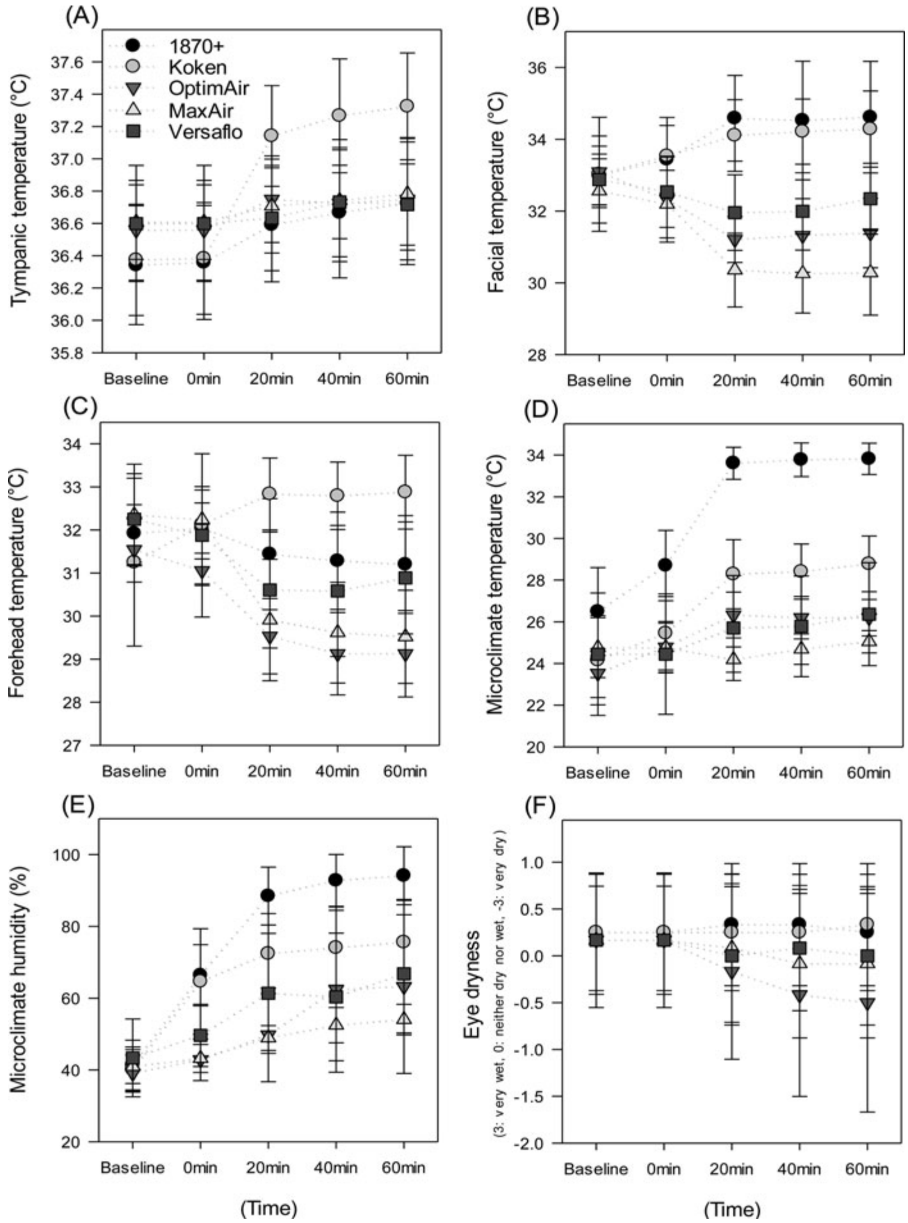

Figure 2. Statistically significant respirator physiological and subjective variables.

the tested respirators in temperate ambient conditions at low-moderate work rates. The study was performed in a laboratory under temperate conditions, so that we cannot comment on the impact of these respirators in hot, humid environments with or without the use of encapsulating protective ensembles (foundry workers, firefighters, healthcare workers treating Ebola in Africa, etc.). It is possible that the use of PAPRs in climates where the entrained air is very warm and humid may result in increases in facial and head temperatures, so that users may experience a greater level of heat stress perceptually or physiologically. Technological improvements in the ability to cool PAPR-delivered air could ameliorate this issue. On the other hand, the ability of such a technologically-advanced PAPRs to cool facial and head skin, coupled to the lack of any significant effect of PAPRs on core temperature, could lead to a dangerous situation wherein face and head comfort masks increasing core temperature. It is possible that a narrow range of numerical responses on the scales/scores utilized in the study could decrease the ability to detect small but important differences between responses, but these scales/scores conform to accepted formats for subjective response research. Comparisons of the Koken with other PAPRs may be somewhat problematic given that it is not a PAPR in the truest sense, but rather a hybrid between a half-facepiece elastomeric air-purifying respirator and a PAPR. The 1870+ model evaluated in the current study is not equipped with an exhalation valve, as are some models of N95 FFRs, that might have impacted some of the study parameters.[25]

However, exhalation-valved respirators are not routinely employed in health care. Lastly, the air currents circulating within the PAPRs could have influenced aural temperatures, though this would not have been the case with the 3M 1870 or the Koken.[20]

Conclusions

In a temperate environment during low-moderate work over 1 hr, wearing a loose-fitting or tight fitting PAPR does not impact cardiopulmonary variables (SpO_2, $tcPCO_2$, HR, RR) nor perceptions of breathing effort, breathing discomfort, and ratings of perceived exertion differently than wearing an N95 FFR. Loose-fitting and tight-fitting full facepiece PAPRs ameliorate exercise-induced increases in facial skin temperature covered by the respirators compared with an N95 FFR and a half-facepiece tight-fitting hybrid PAPR, but this does not result in a statistically significant decrease in perceptions of facial heat or overall body heat. Tympanic temperature may be significantly increased with a hybrid PAPR that is not contiguous with its shroud. Additional research is necessary to determine the effect of these respirators on wearers in hot, humid environments. Use of PAPRS in healthcare environments requires further research and must weigh advantages (greater protection factors, minimal cardiopulmonary impact, etc.) and disadvantages (cost, impact on the use of some medical equipment [stethoscope, ophthalmoscope], etc.).

Disclaimer

The findings and conclusions in this article are those of the authors and do not necessarily represent the views of CDC/NIOSH/NPPTL. Mention of commercial products does not constitute endorsement by CDC/NIOSH/NPPTL.

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