

Quantifying the Heat Stress Attributable to Respirator Wear

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ABSTRACT

For the U.S. military, recent respirator development efforts advocate, among others, designing for a reduced respirator thermal load. However, quantitative data that defines the thermal load attributable to a respirator is limited. Therefore, a study was performed to quantify the effects of respirator wear on physiological responses during heat stress. Five subjects aged 36.0 ± 2.9 years completed 120 min trials consisting of treadmill walking, flight simulation, and performance of cognitive tasks in a warm environment (33.9 ± 0.2 °C dry bulb and 24.3 ± 3.4 °C wet bulb temperatures) under one condition of respirator wear and one condition without a respirator. The respirator trials involved wear of a tight-fitting, powered air-purifying respirator (PAPR). Subjects wore one-piece cotton coveralls over shorts and a T-shirt for both test trials. In general, core temperatures (T_C) increased throughout heat exposure trials. However, both T_C and mean weighted skin temperatures (mean T_{SK}) were statistically similar between the masked and unmasked conditions during testing. At the end of heat exposure sessions, no differences in average core temperatures, heart rates, mean T_{SK} , sweat rates, or heat storage rates were observed between the unmasked and masked conditions. Subjective scores for thermal sensation of the face and overall body comfort differed significantly between conditions, indicating that subjects' faces felt warmer and they experienced greater discomfort during respirator wear. Collectively, these findings suggest that there is no measurable thermal load attributable to a respirator alone other than subjective feelings of warmth and discomfort.

Keywords: powered air-purifying respirator, heat stress, physiological responses, comfort rating

INTRODUCTION

Wearing a complete chemical and biological (CB) protective ensemble reduces the physiological strain that a person can tolerate during heat stress (Montain *et al.*, 1994). However, data that adequately quantifies the relative contribution of a respirator to the overall thermal load associated with full encapsulation does not exist. Respirator designers need to know the amount of heat load due to a respirator under various conditions of work and environmental exposures before the issue can be addressed in the development of next generation respirator systems, whether they are for military or commercial applications. Technical shortcomings and the limited number of thermal stress studies that have reported mask-only thermal burden data make it difficult to determine just how much thermal stress is associated with wearing a respirator (James, 1984, Martin and Calloway, 1974, Martin and Goldman, 1972, and Robinson and Gerking, 1945). For example, Robinson and Gerking (1945) assessed physiological responses of mask wear during exercise in the heat, but only two subjects participated in their study. Likewise, even though semi-empirical efforts to quantify mask thermal burden have been helpful in drawing conclusions regarding recent mask design and development efforts, a reliable definition of the issue has yet to be realized. Therefore, a study was performed to quantify the effects of respirator

wear on the physiological responses during heat stress. Specifically, this study assessed thermoregulatory responses to wear of a tight-fitting, powered air-purifying respirator (PAPR) during heat stress.

METHODS

Test Participants

Five male subjects aged 32 to 39 years volunteered for this study. All subjects were healthy and free of coronary risk factors, as determined by completion of a medical history questionnaire and physical examination. Subject characteristics were as follows (mean $\pm$ standard deviation (SD)): age, 36.0 ± 2.9 years; weight, 87.7 ± 3.4 kg; height, 178.7 ± 5.2 cm; maximal oxygen consumption, 2.41 ± 0.44 L $\cdot$ min⁻¹; and trait anxiety, 27.7 ± 5.0 . All subjects reported prior experience with use of respirators, however none of them used respirators on a daily basis. A written statement of voluntary consent was obtained from each volunteer before testing began.

Determination of Treadmill Settings

Prior to commencement of respirator wear trials, each subject completed a test to determine maximal oxygen consumption ($\dot{V}O_{2\max}$) using an incremental treadmill exercise protocol. Briefly, subjects were prepped for heart rate monitoring prior to administration of the $\dot{V}O_{2\max}$ test. Subjects wore a half-mask (Rudolph 7910, Hans Rudolph, Inc.) commonly used as an alternative to the mouthpiece and nose-clip configuration used for the collection of respired gases in many exercise performance studies. After a five-minute warm-up period of level treadmill (Trackmaster TM 500E, JAS Manufacturing) walking at a pace that required brisk walking but not jogging, the grade of the treadmill was increased incrementally every three minutes until the volunteer terminated the test. Once subjects recovered from their $\dot{V}O_{2\max}$ test, they were asked to walk on the treadmill for up to 10 minutes so that determinations of speeds and grades needed to elicit 40% of $\dot{V}O_{2\max}$ could be determined.

For all $\dot{V}O_{2\max}$ tests, ventilatory measurements of tidal volume, respiration rate, and minute ventilation were obtained from a flowmeter (K-520 transducer, KTC-3-D compensator, and S-430 spirometric module, K.L. Engineering) mounted to the end of expiratory tubing attached to a mixing chamber. Respired gas concentrations were measured from the mixing chamber with a respiratory mass spectrometer (MGA 1100, Perkin-Elmer). Tidal volume, breathing frequency, minute ventilation, O_2 consumption, and CO_2 production were measured on-line using a customized data acquisition system (SCXI and DAQ board controlled by LabVIEW[®] software, National Instruments). Heart rate was monitored continuously using a bipolar 3-lead ECG (Quinton Q3000 ECG Monitor, Quinton Instrument Co.) during each test.

Computer-Based Tasks

Once treadmill settings required for eliciting the selected work rate were determined, subjects received instructions on the techniques that they would use to complete the computer-based tasks selected for this study. Subjects were given time to practice the methods required to complete the different tasks to become familiar with what would be displayed on the computer screen, which keys would be used, and what the rules were for each task. The principal investigator provided step-by-step instructions to each subject and answered subject questions that arose during the orientation session.

The three computer-based applications used in this study were the Walter Reed Performance Assessment Battery (PAB) (Thorne *et al.*, 1985), the State-Trait Anxiety Inventory (STAI) (Spielberger *et*

al., 1983), and a flight simulation application. The PAB is a computerized research tool that contains various tasks that assess subject mood state, anxiety, and cognitive function. For this investigation, the PAB was configured to include the mood scale, serial addition/subtraction, logical reasoning, four-choice serial reaction time, and 10-choice reaction time tasks. All tasks were presented via a computer (Dell PC, SVGA color monitor, and INSTACAL CIO-CTR5 timer board). The mood scale task consisted of a three-point scale (1-3) with the word anchors of "not at all," "somewhat or slightly," and "mostly or generally." Thirty-six adjectives that describe different mood states were presented in random order to the subject. Examples of these include "calm" and "energetic." Subjects responded by depressing the number that best described the degree to which they currently felt in relation to the presented adjective. The 36 adjectives represented the six factor scores of Anger, Happiness, Fear, Depression, Activity, and Fatigue. An overall mood disturbance score was obtained from the factor scores.

The PAB serial addition/subtraction task is a mental arithmetic task requiring sustained attention. Two randomly selected digits and either a plus or minus sign were displayed sequentially in the same screen location, followed by a prompt symbol. The subject performed the indicated operation and entered the least significant digit of the result (e.g., "7, 5, +" equals 12, so enter 2). However, if the displayed operation resulted in a negative number, subjects were required to add 10 to the negative value and then enter the result of that computation (e.g., "5, 10, -" equals negative 5, add 10, which equals 5, so enter 5). Scores were provided for the number of correct and incorrect responses, speed, and throughput (correct responses $\cdot$ min⁻¹).

Logical reasoning involved an exercise in transformational grammar. Sustained subject attention was also an aptitude needed for this task. The letter pair "AB" or "BA" was presented along with a statement describing the order of the letter pair (e.g., "B follows A" or "A is not preceded by B"). The subject had to decide whether the statement was the "Same" or "Different" from the letter pair and respond by pressing the "S" or "D" key. If no valid response occurred after 30 s, a beep was sounded, the screen went blank, and the next trial was presented. Summary data of this task were: 1) number and percent correct, and 2) reaction time means and standard deviations for total responses, correct responses, and incorrect responses.

For the PAB four-choice serial reaction time task, a red square appeared in one of four boxes positioned in the center of the computer screen and the subject pressed a corresponding button on the numeric keypad as quickly and as accurately as possible. Summary scores included the mean and standard deviations for all correct responses, incorrect responses, the number of correct and incorrect responses, and the percentage of correct responses. The 10-choice reaction time task was a simple reaction time task that also served as a control task for serial addition/subtraction, and as a practice doubler to hasten stability on the keypad. A single number from 0-9 was presented in the center of the screen and subjects responded by pressing the corresponding number on the numeric keypad as quickly as possible.

The State-Trait Anxiety Inventory comprises separate self-report questionnaires for measuring state and trait anxiety. Neither the state or trait portions of the inventory have time limits for completion. The trait anxiety inventory (TANX) is a 20-item scale that evaluates how respondents *generally* feel, whereas the state anxiety inventory (SANX) is a 20-item scale that assesses how people feel "*right now*, at this moment." An in-house computer program was used to administer and score both the state and trait anxiety questionnaires.

Two commercially available flight simulation software packages were used for this investigation: Jane's® F-15 and Jane's® Longbow Anthology. During the orientation session, the principal investigator briefly demonstrated each flight simulation package. Following the demonstration, subjects were given the opportunity to try each simulation and then were asked to choose the simulation that they would prefer to use during the heat exposure trials. The flight simulation task was used mainly as a low-intensity computer operation task for this investigation.

Experimental Conditions

The U.S. Air Force (USAF) Aircrew Eye/Respiratory Protection (AERP) equipment was used for the mask wear trial. The AERP equipment consisted of a chemical protective mask-hood assembly, MBU-19/P breathing subsystem, a blower subsystem, and a communication subsystem. The AERP mask-hood assembly is best classified as a tight-fitting, powered air-purifying respirator (PAPR). The blower supplied filtered air at ambient temperature. The communication system was connected to the helmet and AERP to aid communication between the test administrators and the test subject. For this study, the AERP was operated in ground mode, which is defined as follows: The blower supply hose was connected to the oxygen manifold filter canister using a pigtail adapter; the control knob of the blower assembly was positioned halfway between the off and full speed settings, providing air to the AERP mask-hood system at a rate of approximately 6 cubic feet per minute; and the crossover valve knob was turned to the horizontal position. Therefore, filtered ambient air was supplied to the AERP mask-hood assembly as shown in Figure 1. However, during heat exposure trials, subjects were permitted to adjust the crossover valve knob to direct more of the air supply to the AERP lens for demisting, if necessary.

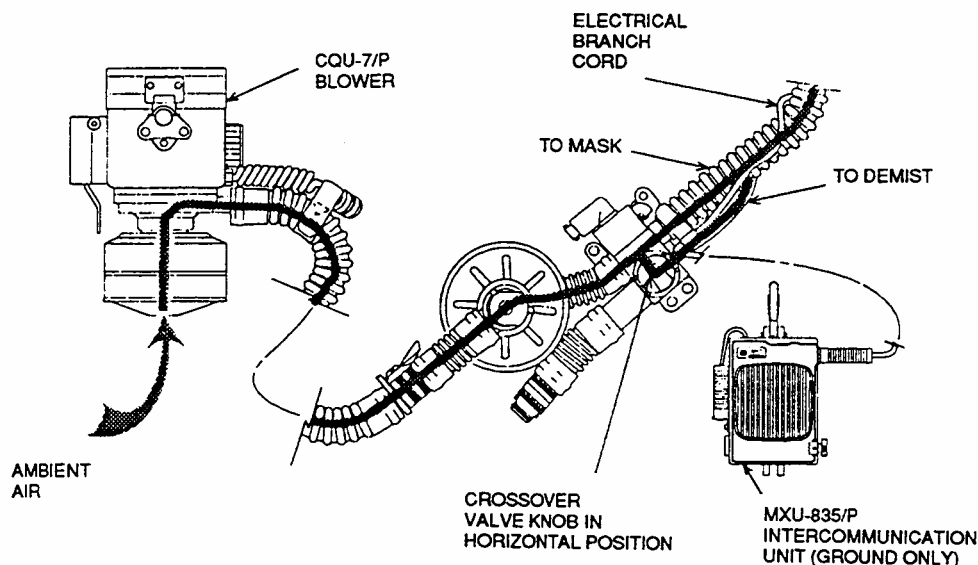


Figure 1. MBU-19/P Breathing System air flow in ground operating mode.

For this study, volunteers completed one trial with the AERP equipment and one without. Subjects wore one-piece cotton coveralls over shorts and a T-shirt for both test trials. The coveralls were used instead of the standard battle dress uniform (a.k.a. BDU) or flight suit because they were readily available and easy to launder. In addition, athletic socks and sneakers were substituted for standard issue military socks and boots. Subjects wore the USAF HGU-55/P aircrew helmet for all test conditions (Figure 2). The AERP hood-mask assembly is worn with the helmet using standard offset bayonet connectors. Presentation of conditions was randomly assigned and volunteers were exposed to only one test condition on any given day. Test days were separated by at least 24 hours. Subjects were instructed to get adequate rest the night before each trial, to eat a light breakfast or lunch, and to drink plenty of fluids excluding caffeine and alcohol before reporting for their test sessions.

Experimental Procedures and Measurements

The data collection procedures for the two test iterations were identical. On the evening prior to a scheduled test, subjects ingested a telemetric temperature sensor or pill (CorTemp™, HTI Technologies, Inc.) that was used for monitoring body core temperature (T_C). The CorTemp™ disposable temperature sensors are 2 cm in length and 1.2 cm in diameter and consist of a temperature sensitive quartz crystal oscillator with a silver oxide battery encapsulated in epoxy and covered with silicone rubber. In the gastrointestinal tract, the quartz within the sensor vibrates at a frequency that varies according to body temperature, producing a magnetic flux and transmitting a signal harmlessly through the body to a remote monitor/recorder. Upon arrival to the laboratory, a data receiver/logger (CorTemp™ 2000 Ambulatory Recorder, HTI Technologies, Inc.) was used to confirm that the subject had indeed ingested the temperature pill as instructed and to ensure that the device was functioning. The CorTemp™ 2000 is a miniature unit with a belt-clip that requires no catheters, probes or direct connecting wires for displaying or recording T_C . Temperature readings from the temperature sensors were recorded to the nearest 0.01°C.



Figure 2. Front and side views of the standard HGU-55/P aircrew helmet.

Once operation of the temperature pill was confirmed, subjects ingested 300 ml of water and were given the opportunity to use the restroom. An initial nude (i.e., dressed only in underwear) body weight was then obtained using a calibrated electronic scale (DIGI Grand Scale, DIGI Matex, Inc., accuracy ± 10 g) and subjects were prepped for heart rate monitoring. Heart rate and rhythm were monitored continuously throughout heat exposure trials using a telemetry system (Eaton Medical Telemetry System 4Si, EatonCare). Following placement of heart rate electrodes, subjects were fitted with four temperature probes for recording skin surface temperatures. Temperature thermistor probes (Model 409B, YSI, Inc.) were attached to the chest, dorsal surface of the left forearm, lateral left calf, and upper lip using self-adhering foam patches (TempHeart, YSI, Inc.). A scanning thermistor thermometer (Cole-Parmer 5-Channel Thermistor Thermometer, Cole-Parmer) that read temperatures to the nearest 0.1°C was used for monitoring skin temperatures. All skin temperature probes were tested to verify proper functioning before commencement of a test session.

Subjects then dressed for the scheduled test configuration with assistance from test personnel. Once dressed, subjects performed a regimen of treadmill walking and computer generated test batteries

in an environmental test chamber. The environmental chamber was set for 35°C dry bulb temperature for all trials. At the beginning of a heat exposure session, subjects entered the chamber and were seated in front of a computer. Once seated, baseline measurements of T_c , skin temperatures, and heart rate were recorded. Subjects were then asked to provide baseline subjective ratings of perceived exertion (RPE) (Borg, 1982) and thermal sensation (Gwosdow *et al.*, 1989) using specific subjective scales. Subjects also rated comfort of the following using the breathing apparatus comfort (BAC) scale (Abadie and Carroll, 1993): face, nosecup, head, breathing (i.e., airflow resistance), and overall comfort of the complete clothing and mask ensemble. Thermal sensation ratings of the subject's face and whole body were obtained with and without the AERP equipment.

After baseline data were obtained, timing of the two-hour heat exposure trial began once subjects initiated the first session of the PAB test battery and completed the state anxiety questionnaire. This first task period lasted for 10 minutes. Subjects were seated during performance of the PAB/state anxiety test period and remained seated if the tasks were completed before the 10-minute period transpired. Following this initial 10 minutes of heat exposure, subjects completed 20 minutes of treadmill walking at an exercise intensity of 40% of $\dot{V}O_{2\max}$. Speed and grade of the treadmill were set to the levels established following a subject's $\dot{V}O_{2\max}$ test. Treadmill speeds were set at a walking pace for all subjects. After treadmill exercise, subjects were again seated before the computer and performed the tasks of the selected flight simulation software package for 30 minutes. The PAB/state anxiety session, treadmill walk, and flight simulation tasks were then repeated.

An experimental heat exposure session was terminated when the 120-minute test period transpired, a subject reached the predetermined endpoint criteria for T_c (39.0 °C), heart rate exceeded 180 beats·min⁻¹, or a subject requested to terminate the session or was unable to continue. Following cessation of the second flight simulation period, subjects completed one final PAB/state anxiety session. Subjects then exited the environmental chamber and were assisted with removal of the test clothing and/or mask. Subject heart rate and T_c were monitored during this time until the on-site medical monitor indicated that monitoring was no longer necessary. A final nude (i.e., dressed only in underwear) body weight was then obtained and subjects were free to drink ad libitum.

Subjects drank approximately 300 ml of water every 20 minutes throughout the heat exposure period to prevent excessive loss of body weight and dehydration during exercise. One-quart canteens with specialized canteen caps that permitted connection with the AERP drinking tube were used for all trials. Canteen weights were recorded to the nearest 0.01 g using a calibrated scale (Sartorius Balance L2200 S, Brinkmann Instruments Co.) before and after each drinking period and total water replacement was calculated after each test session. Total body sweat production and sweat rate were calculated as the difference between a subject's final and initial nude body weights, adjusted for fluid intake.

Body core temperature (T_c) was monitored using the CorTemp™ disposable temperature sensors and the CorTemp™ 2000 recorder. This system has been shown to provide a valid measure of core temperature during conditions of increasing body temperature (O'Brien *et al.*, 1998). The unique calibration and serial numbers of each sensor were programmed into the recorder enabling the device to correctly interpret the sensor oscillations and convert them into temperature readings. The disposable temperature sensors were delivered factory calibrated with a guaranteed accuracy of $\pm 0.1^\circ\text{C}$. However, the accuracy and precision of the calibration of the sensors was confirmed in-house for multiple samples selected from each ordered lot of the sensors. Selected sensor samples were placed in a water bath (TCS-100 Thermometry Calibration System, Ever Ready Thermometer Co., Inc.) and sensor temperatures recorded by the CorTemp™ 2000 recorder were compared to water temperature readings obtained from a National Institute of Standards and Technology (NIST) certified mercury thermometer. The correlation coefficient between water bath temperature and recorder temperature was greater than 0.98 for each pill, which indicated that the factory calibrations were acceptable. Temperature readings were recorded during every minute of heat exposure and later downloaded to a computer after completion of data collection.

Mean skin temperature (mean T_{sk}) was calculated from surface temperatures recorded from the chest, arm, and calf using the Burton (1935) equation, where mean $T_{sk} = 0.5 \text{ chest} + 0.14 \text{ arm} + 0.36 \text{ calf}$. Skin temperatures were recorded every five minutes of testing. Each thermistor probe was calibrated

prior to commencement of the study using the scanning thermistor thermometer, water bath, and NIST certified mercury thermometer. All probes calibrated within 0.1°C of the standard.

The rate of body heat storage for each mask and clothing configuration was calculated using the formula (Craig *et al.*, 1954):

$$\text{Heat Storage Rate (kcal}\cdot\text{m}^{-2}\cdot\text{h}^{-1}) = M \cdot S \cdot \Delta\text{MBT} \cdot \text{SA}^{-1}$$

where: M = body weight (kg),

S = the specific heat constant ($0.83 \text{ W}\cdot\text{h}^{-1}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$),

ΔMBT = the change in mean body temperature ($0.8\cdot T_{\text{C}} + 0.2\cdot \text{mean } T_{\text{sk}}$), and

SA = surface area (m^2).

Total heat accumulation was found by multiplying the heat storage rate by the length of a test for each test session. Heart rate and rhythm were monitored continuously throughout heat exposure trials and recorded on-line in five-minute intervals using a telemetry system. On-site contract medical personnel monitored the heart rhythm tracings. A portable wet-bulb black globe (WBGT) monitor (RSS-214 WiBGeT, Imaging and Sensing Technology) was used to monitor dry-bulb (T_{db}), wet-bulb (T_{wb}), and indoor WBGT temperatures in the environmental chamber. Environmental temperatures were recorded at 10-minute intervals.

Subjective RPE, BAC, and thermal sensation scores were obtained following initial donning of the clothing and/or respirator at 10-minute intervals up to the end of each heat exposure session. As previously stated, subjects rated comfort of the following respirator factors using the BAC scale: face, noseclip, head, breathing, and overall comfort of the complete ensemble. Ratings of noseclip and breathing comfort were self-explanatory. For face comfort, subjects were instructed to consider the comfort of the hood-mask on the whole face where components of the system contacted the face. For head comfort, subjects were advised to focus on the comfort of the hood-mask on the head beneath the helmet. For the unmasked condition, head comfort served as a measure of helmet comfort only. When asked to rate overall comfort, subjects were instructed to take into account all components of the equipment on the head and face as well as the clothing.

Physiological and cognitive responses during heat exposure periods were analyzed using an analysis of variance ANOVA for the independent variables of time and mask condition. Scheffe's *post-hoc* analysis was computed to determine significant differences between group means if a significant F statistic was initially obtained. Independent-samples t -tests were conducted for comparisons of unmasked and masked group means for pre and post-test data. All statistical computations were performed using SPSS 7.5 for Windows. Statistical significance was accepted at the $p < 0.05$ level. Unless otherwise stated, data are presented as means $\pm$ SD.

RESULTS

No differences in T_{db} , T_{wb} , or WBGT temperatures in the test chamber were observed between the two experimental conditions. Independent of experimental condition, T_{db} averaged $33.9 \pm 0.2^{\circ}\text{C}$ (approximately 93°F), T_{wb} averaged $23.6 \pm 3.0^{\circ}\text{C}$ (approximately 74°F), and WBGT temperatures averaged $27.1 \pm 2.2^{\circ}\text{C}$ (approximately 81°F). Based on average T_{db} and T_{wb} values, the relative humidity within the environmental chamber was approximately 47% for the heat exposure trials.

Subjects completed the entire 120-minute heat exposure test period for both the no mask with coveralls and AERP with coveralls conditions. Table I presents average data for the unmasked and masked configurations obtained at the end (i.e., 120 minutes) of heat exposure sessions. No significant differences between the no mask with coveralls and AERP with coveralls condition were found for any of these test variables.

Table I. Core and mean skin temperatures, heart rate, sweat rate, heat accumulation, and heat storage rate at the end of heat exposure (i.e., at 120 minutes; n=5)

Measurement (units)	No Mask	AERP
Core Temperature ($^{\circ}\text{C}$)	37.4 ± 0.3	37.0 ± 0.8
Mean Skin Temperature ($^{\circ}\text{C}$)	34.5 ± 0.6	35.0 ± 0.3
Lip Temperature ($^{\circ}\text{C}$)	35.4 ± 0.1	35.6 ± 0.3
Heart Rate ($\text{beats}\cdot\text{min}^{-1}$)	75 ± 11	77 ± 5
Sweat Rate ($\text{g}\cdot\text{min}^{-1}$)	7.2 ± 3.0	9.3 ± 4.1
Heat Accumulation ($\text{kcal}\cdot\text{m}^{-2}$)	19.1 ± 11.7	31.1 ± 11.5
Heat Storage Rate ($\text{kcal}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$)	9.6 ± 5.8	15.5 ± 5.8

Note: Values are mean $\pm$ SD.

Figure 3 graphs minute average T_C from the start of each heat exposure condition to five minutes post-test. In general, T_C increased throughout heat exposure trials. Core temperatures were statistically similar between the masked and unmasked experimental conditions at each minute for the entire measurement period. In addition, analysis of the slopes of the least square regressions indicated that the increases in T_C throughout testing were identical between conditions.

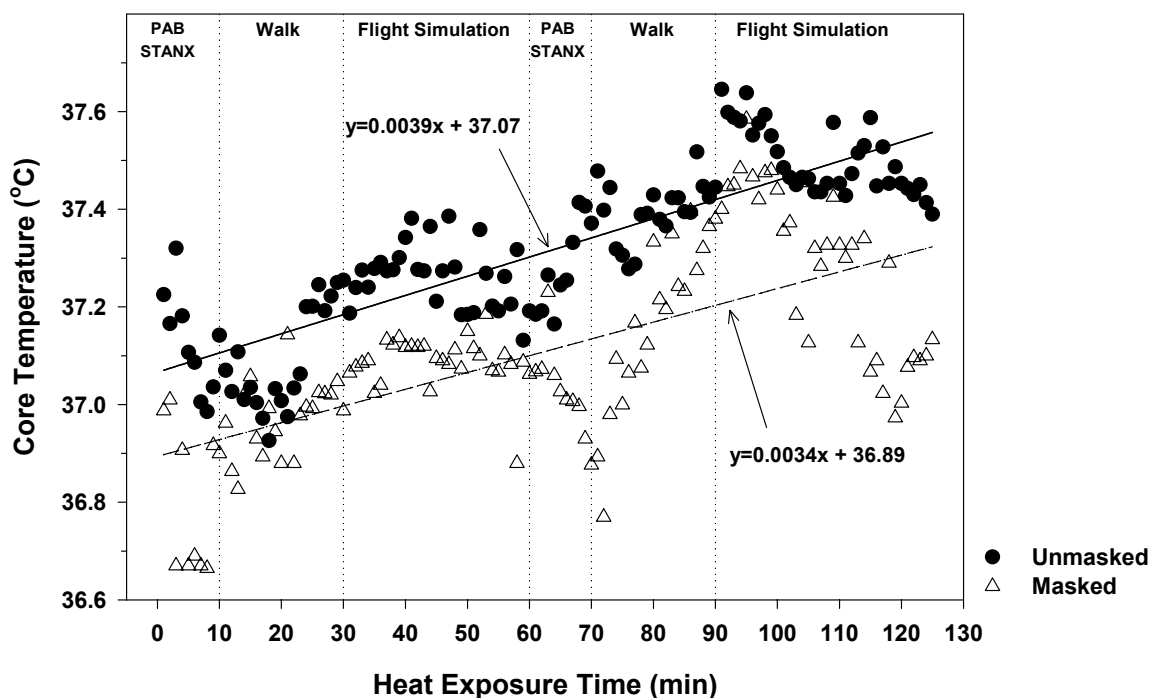


Figure 3. Minute-by-minute core temperatures for the unmasked and masked overall conditions. Linear regressions are drawn for each condition.

Average mean T_{sk} over time was generally higher for the masked compared to the unmasked experimental condition during the 120-minute heat exposures sessions (Figure 4). However, mean T_{sk} were statistically similar at all measurement periods over the course of the 120-minute test sessions. The highest mean T_{sk} values were observed during the treadmill walking periods. Average heart rate responses for the masked and unmasked experimental conditions followed a pattern similar to mean T_{sk} and no differences were found between conditions throughout the heat exposure sessions.

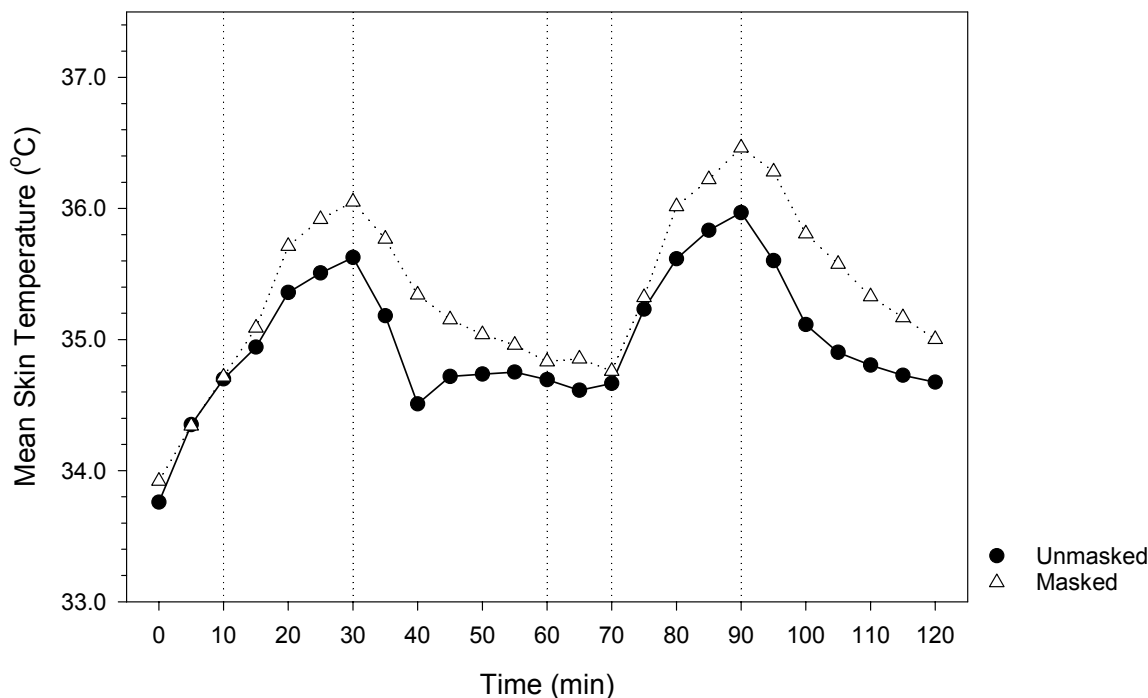


Figure 4. Mean skin temperatures obtained at 5-minute intervals during heat exposure. Vertical lines denote the different periods of task performance (reference Figure 3).

Upper lip temperatures varied considerably over time and differences between experimental conditions varied depending on the time of measurement (Figure 5). In general, recorded lip temperatures were lower during trials with the AERP respirator compared to the unmasked condition. The greatest differences in average lip temperatures between conditions were observed during the two treadmill walking periods of the heat exposure session and these differences were significant at the 15 and 20-minute measurement periods. Average lip temperature did not change significantly from the beginning to the end of heat exposure during the unmasked trial, but lip temperature increased significantly from 34.4 ± 0.6 °C at the start of heat exposure to 35.6 ± 0.3 °C at the end of testing for the AERP wear condition. Independent of time, lip temperatures averaged 35.5 ± 0.4 °C for unmasked trials and 35.1 ± 0.7 °C for masked trials. The difference between these values was significant.

Subjective RPE scores did not differ between experimental conditions at any time during heat exposure and average scores were similar between conditions when compared by task. Independent of experimental condition, RPE scores averaged 9.7 ± 2.1 during completion of the PAB and state anxiety tasks, 9.3 ± 1.7 during flight simulation, and 13.6 ± 2.4 during treadmill walking. Average RPE scores were significantly ($p < 0.001$) higher during walking compared to the other heat exposure tasks.

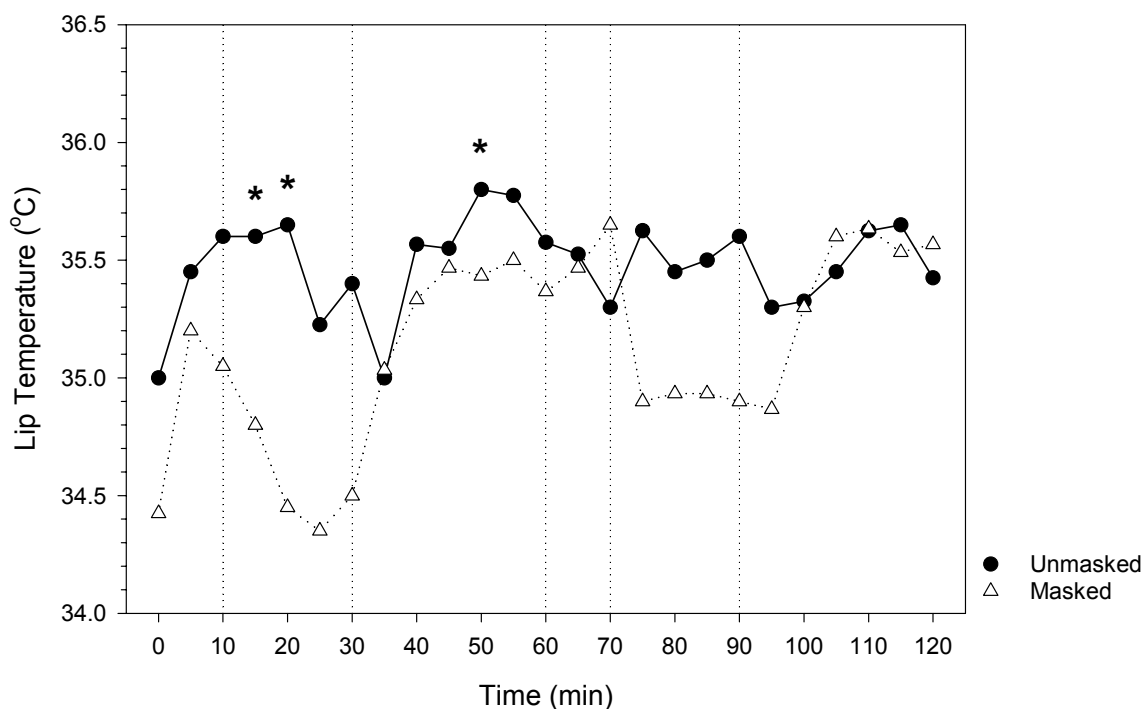


Figure 5. Average upper lip temperatures over time for the Unmasked and Masked conditions. Vertical lines denote the different periods of task performance (reference Figure 3). * = Significant difference between groups.

Facial thermal sensation ratings were higher for the AERP wear experimental condition compared to the unmasked trials for the duration of the heat exposure period (Figure 6). Subjective facial thermal sensation scores were significantly higher for the masked condition at 30, 50, 80, 90, and 110 minutes of heat exposure, indicating that subjects' faces felt significantly warmer during AERP wear at these different measurement periods. Average facial thermal sensation scores did not change significantly from the beginning to the end of heat exposure for either test condition. In contrast to facial thermal sensation, whole body thermal sensation scores were identical between masked and unmasked conditions throughout heat exposure trials.

On average, breathing comfort scores were lower during AERP wear at each measurement period of heat exposure compared to the unmasked condition (Figure 7) indicating that subjects experienced more breathing discomfort during respirator wear. Breathing comfort scores differed significantly at the start of testing and from 40 to 70 minutes and 100 to 120 minutes of heat exposure. Even though the act of breathing was perceived to be more uncomfortable during wear of the AERP for the majority of the heat exposure period, average BAC scores indicated that breathing with the respirator on was still "Fairly comfortable." Average breathing comfort scores did not change significantly from the beginning to the end of heat exposure for either test condition. Independent of time, breathing comfort scores averaged 8.8 ± 1.6 for unmasked trials and 5.8 ± 1.1 for masked trials. The difference between these values was significant.

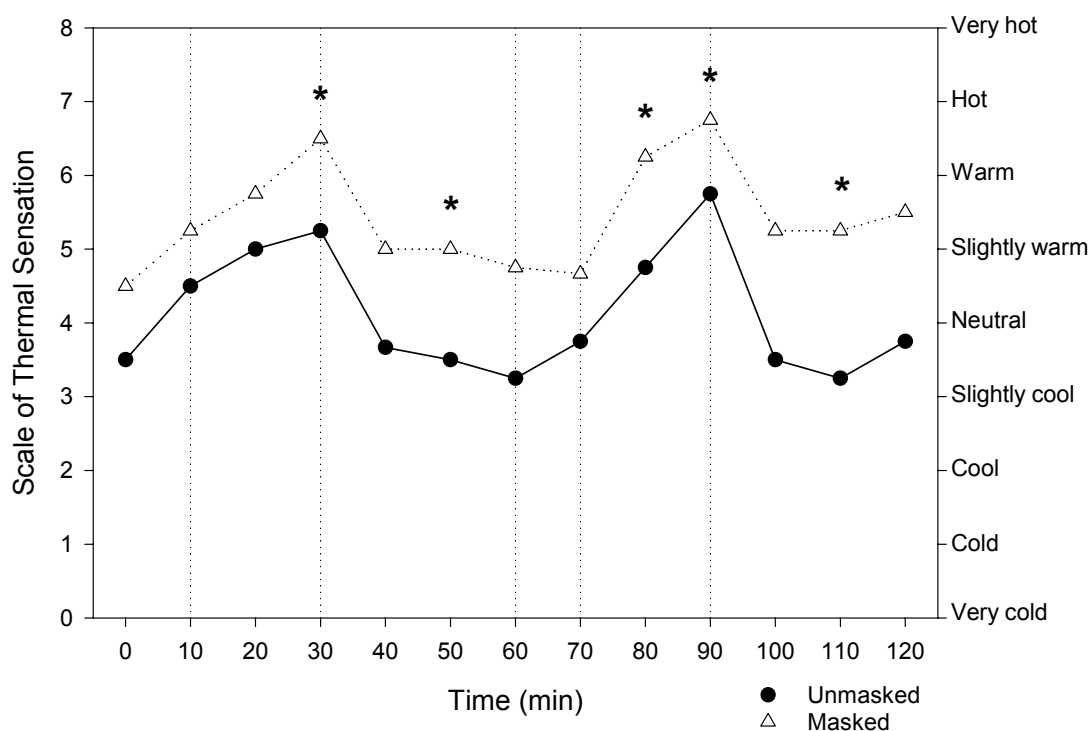


Figure 6. Thermal sensation ratings of the face during heat exposure. Vertical lines denote the different periods of task performance (reference Figure 3). * = Significant difference between groups.

Subjective ratings of head comfort were lower, but not significantly, throughout heat exposure trials for the AERP wear condition compared to the unmasked condition. Average head comfort scores fell within the narrow range of “Fairly uncomfortable” to “Fairly comfortable” on the BAC scale. Nosecup comfort ratings decreased significantly from the beginning to the end of heat exposure for the AERP condition (5.5 ± 1.0 to 3.0 ± 1.2 ; $p = 0.02$). However, face comfort scores were relatively unchanged during testing with the AERP.

Subjective ratings of overall comfort were lower throughout heat exposure trials for the AERP wear condition compared to the unmasked experimental condition indicating that subjects were generally more uncomfortable during respirator wear (Figure 8). Subjective responses about overall comfort differed significantly between conditions after 60, 70, and 120 minutes of heat exposure. As with ratings of breathing comfort, average ratings for overall comfort did not change significantly from the beginning to the end of heat exposure for either test condition. Independent of time, overall comfort scores averaged 6.9 ± 1.9 for unmasked trials and 5.2 ± 0.8 for masked trials. The difference between these values was significant.

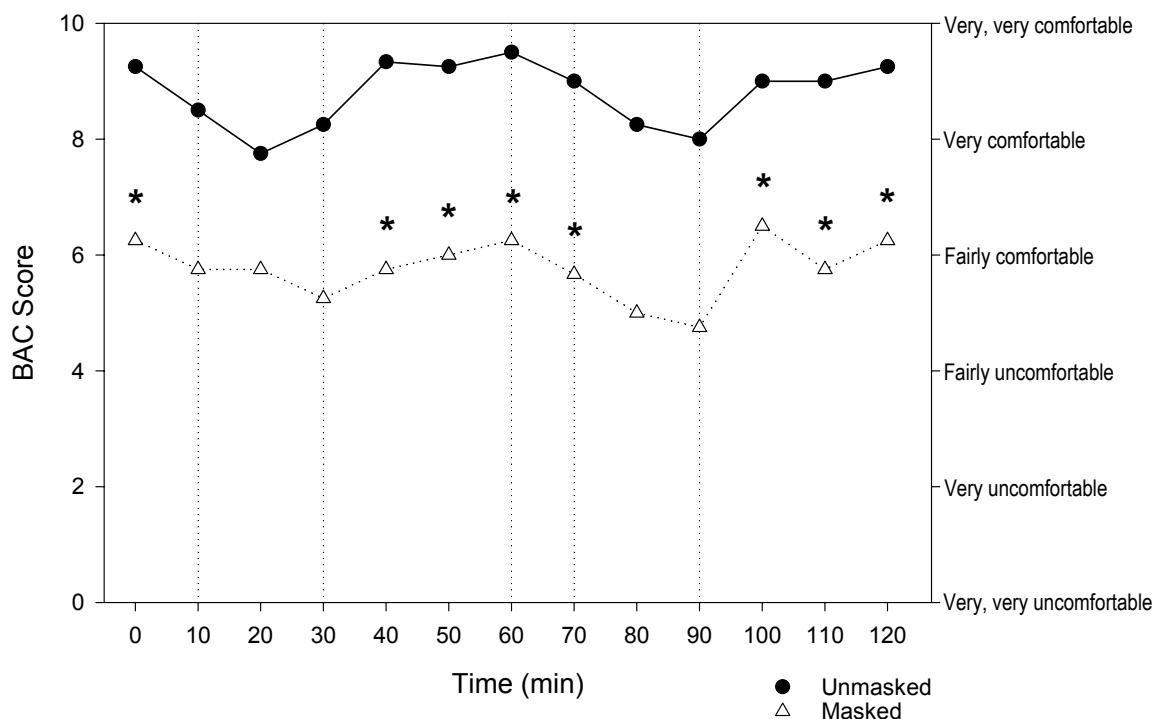


Figure 7. Average breathing apparatus comfort (BAC) scores for breathing comfort recorded over time for each experimental condition. Vertical lines denote the different periods of task performance (reference Figure 3). * = Significant difference between groups.

Participants in this study demonstrated stable individual differences in anxiety proneness by exhibiting relatively low trait anxiety scores (27.7 ± 5.0). Average state anxiety scores did not differ between or within experimental conditions before, during, or after heat exposure. Independent of the time of measurement, state anxiety scores averaged 31.3 ± 7.3 for the unmasked condition and 34.3 ± 7.4 during the masked condition. Results of the PAB logical reasoning task indicated that response accuracy (% correct), speed (responses $\cdot$ min $^{-1}$), and throughput (correct responses $\cdot$ min $^{-1}$) were identical within and between experimental conditions before, during, and following heat exposure. These results suggest that AERP wear did not affect subject logical reasoning ability during heat exposure.

As for the other PAB reaction time tasks, response accuracy, speed, and throughput were statistically similar within and between experimental conditions before, during, and following heat exposure for the serial addition and subtraction task. On average, response accuracy ($91.6 \pm 12.1\%$), speed (47.5 ± 21.7 responses $\cdot$ min $^{-1}$), and throughput (45.1 ± 22.4 correct responses $\cdot$ min $^{-1}$) were lower under the unmasked condition compared to the masked condition independent of measurement period. However, the differences between conditions were not significant. These findings indicate that AERP wear had no significant impact on subject attention during heat exposure. Likewise, mood scale data did not differ between experimental conditions before, during, and following heat exposure, suggesting that wear of the AERP did not alter the mood state of the test participants.

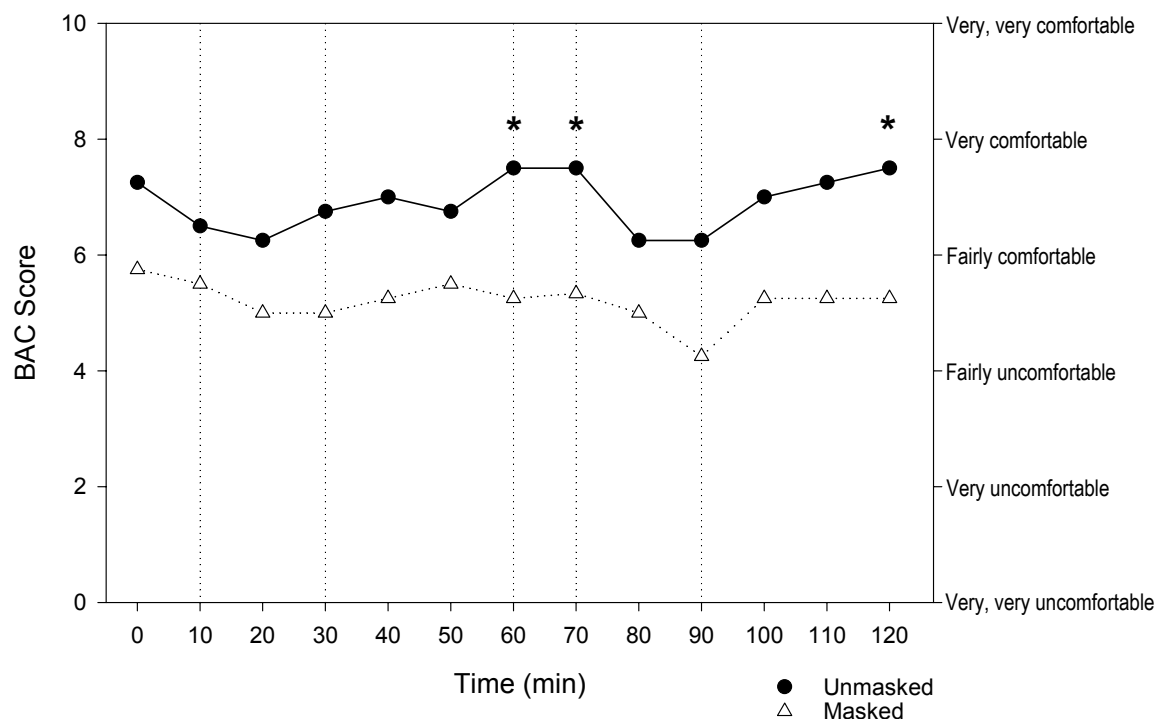


Figure 8. Average overall comfort scores recorded over time for each experimental condition. Vertical lines denote the different periods of task performance (reference Figure 3). * = Significant difference between groups.

DISCUSSION

This study attempted to quantify the effects of respirator wear in and of itself on select physiological and psychological responses during heat stress. Several previous studies have made attempts to do the same with differing results. For tests that were conducted without the use of protective overgarments, others have reported that wear of a full-facepiece, negative pressure respirator with an impermeable hood elevates whole body sweat rate and mean skin temperatures above no mask conditions during exercise (Martin and Calloway, 1974, Martin and Goldman, 1972, and Robinson and Gerking, 1945). Likewise, most reports state that heart rates tended to be higher with a mask on. In contrast, no statistical differences in sweat rates, heart rates, or mean skin temperatures were found between the masked and unmasked conditions of this investigation for our limited number of test participants. Core temperature responses were also similar between these conditions, a finding that has been corroborated by others (Martin and Goldman, 1972 and Robinson and Gerking, 1945), and total body heat accumulation and heat storage rates did not differ between conditions. These findings indicate that under conditions of heat exposure and work, wear of a tight-fitting PAPR such as the AERP caused the same physiological thermal load as was experienced without a respirator.

Gwosdow *et al.* (1989) investigated the relationships between upper lip skin temperature and respirator comfort and between lip temperature and thermal sensation at rest for an air-supplied half-facepiece respirator. They found that respirator thermal sensation and comfort correlated significantly to

lip skin temperature. In addition, these investigators found that as lip skin temperature rose above 34.5°C, subjective ratings of respirator discomfort increased. In the present study, average skin temperatures of the upper lip were at or above 34.5°C throughout the test period for both the unmasked and masked conditions and lip skin temperatures tended to be lower for the unmasked condition. However, unlike Gwosdow *et al.* (1989), we found no correlations for facial thermal sensation, whole body thermal sensation, or any of the subjective comfort parameters with upper lip temperature. Findings reported by Coyne *et al.* (2000), which indicate that facial thermal sensation and respirator comfort are not strongly related to face temperatures during exercise, corroborate our findings. In addition, despite the tendency for higher lip temperatures without the respirator compared to the masked condition, our results showed that facial thermal sensation ratings were higher for the masked condition compared to the unmasked trial for the duration of the heat exposure period. This finding indicates that subjects' faces generally felt warmer during respirator wear even though the objective upper lip skin temperature data appeared to be lower than or equal to values obtained when the mask was worn. Collectively then, our results suggest that respirator comfort and thermal sensation of the face are impacted by more than just upper lip temperatures during exercise and heat exposure.

Generally speaking, subjective responses to the various comfort parameters showed more of a dependence on work task than an effect of experimental mask condition. However, breathing comfort ratings indicated more discomfort under masked conditions throughout most of the heat exposure session. Even so, the degree of breathing discomfort with the AERP respirator was not that great considering that average BAC scores indicated that breathing was "Fairly comfortable" throughout the wear period. Caretti reported similar BAC scores for breathing comfort under similar intensity work conditions at room temperature while wearing respirators for one hour (2000) and under somewhat higher work rates during two hours of wear (1999). Therefore, it appears that breathing discomfort recorded during the current study was due solely to wearing the respirator and was not impacted by heat exposure.

Subjective ratings of overall comfort were also lower throughout heat exposure trials for the AERP wear condition compared to the unmasked experimental condition indicating that subjects were generally more uncomfortable during respirator wear while in the heat. Even though the differences in overall comfort between conditions that were recorded throughout the two-hour heat trials were not as distinct as those found for breathing comfort, nor did the differences reach significance as often, subjects consistently reported greater overall discomfort when wearing the respirator. A significant correlation ($r = 0.57$, $p < 0.05$) between overall comfort ratings and breathing comfort ratings was evident during respirator wear, but not for the unmasked condition, suggesting that the higher level of overall discomfort reported for our masked trials was due in part to breathing discomfort imposed by the AERP.

CONCLUSIONS

Determining the proportion of heat stress caused individually by a protective overgarment and the respirator represents a significant challenge. Insights obtained during this study that address this issue for the respirator development community are summarized as follows: The effect of wearing the AERP system was similar to that produced when the respirator was not worn. No statistical differences in sweat rates, heart rates, mean skin temperatures, or core temperatures were found between the unmasked and masked conditions at the end of heat exposure. Self-reported subjective scores for thermal sensation of the face and overall body comfort differed significantly between conditions, indicating that subjects' faces felt warmer and they experienced greater discomfort during respirator wear. Collectively, these findings suggest that there is no measurable thermal load attributable to a respirator alone other than subjective feelings of warmth of the face and discomfort.

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