ASSESSMENT OF THE THERMAL LOAD ATTRIBUTABLE TO PROTECTIVE MASKS

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Two studies were performed to quantify the thermoregulatory responses to mask wear during heat exposure with and without chemical protective (CP) clothing. A powered air-purifying respirator was worn in one study whereas a negative pressure respirator was worn in the second test. Results suggest that there is no measurable thermal load attributable to just a mask in the absence of CP clothing. Unmasked and masked results during wear of CP clothing differed for each mask type and did not clearly indicate a thermal effect of a mask. Additional findings suggest that the protective suit may be the greatest contributor to physiological thermal load during heat exposure.

INTRODUCTION

There are many possible criteria to use for respirator design. For the U.S. military, recent development efforts advocate, among others, designing for a reduced respirator thermal load. However, quantitative data that defines the thermal load attributable to a respirator in and of itself is limited. 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. Technical shortcomings of many 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.[1-3] In addition, the issue of respirator thermal load may be further clouded by the effects of wearing encapsulating chemical and biological protective clothing.[4] Therefore, two studies have been performed to quantify the effects of respirator wear on the physiological responses during heat stress. Specifically, one study assessed thermoregulatory responses to wear of a tight-fitting, powered air purifying respirator (PAPR) during heat stress, whereas the second study measured thermoregulatory responses during wear of a full facepiece, negative pressure respirator.

EXPERIMENTAL METHODS

1. PAPR HEAT STRESS TEST (TEST 1)

Five healthy male subjects aged 32 to 39 years volunteered for this study. Subject characteristics were as follows (mean ± standard deviation (SD)): age, 36.0 ± 2.9 years; weight, 87.7 ± 3.4 kg; height, 178.7 ±

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5.2 cm; maximal oxygen consumption, 2.41 ± 0.44 L · min^{-1}; and trait anxiety, 27.7 ± 5.0. A written statement of voluntary consent was obtained from each volunteer before testing began. Each subject then completed a test to determine maximal oxygen consumption ($\dot{V}O_{2\,max}$) using an incremental treadmill exercise protocol. Treadmill speed and grade required to elicit between 40-45% of subject's $\dot{V}O_{2\,max}$ were estimated following each 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 40-45% of $\dot{V}O_{2\,max}$ could be determined.

Subjects received instructions on the techniques that they would use to complete the computer-based tasks selected for this study. The three computer-based applications used in this study were the Walter Reed Performance Assessment Battery (PAB),[5] the State-Trait Anxiety Inventory (STAI),[6] and a flight simulation application. The PAB was configured to include a mood scale, serial addition/subtraction, logical reasoning, four-choice serial reaction time, and 10-choice reaction time task. The State-Trait Anxiety Inventory comprises separate self-report questionnaires for measuring state and trait anxiety. Jane's[®] Longbow Anthology flight simulation software package was used as a low-intensity computer operation task for this investigation.

The Aircrew Eye/Respiratory Protection (AERP) protection equipment was used for mask wear trials. The AERP equipment consisted of a chemical protective mask-hood assembly, a nose-cup breathing subsystem, and a blower 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 following heat exposure trials were completed in random order: no mask with cotton coveralls, the AERP with coveralls, no mask with the Joint Service Lightweight Integrated Suit Technology (JSLIST) protective overgarment, and wear of the AERP with the JSLIST. Test days were separated by at least 24 hours. 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). 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. Temperature readings were recorded during every minute of heat exposure and later downloaded to a computer after completion of data collection.

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 heat 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 temperature thermistor probes (Model 409B, YSI, Inc.) for recording skin surface temperatures. Mean weighted skin temperature (MWST) was calculated from surface temperatures recorded from the chest, arm, and calf using the Burton[7] equation. Skin temperatures were recorded every five minutes of testing using a scanning thermistor thermometer (Cole-Parmer 5-Channel Thermistor Thermometer, Cole-Parmer).

Once dressed for the scheduled test configuration, subjects performed a regimen of treadmill walking and completion of computer test batteries in an environmental 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)[8] and thermal sensation[9] using specific subjective scales. Subjective RPE and thermal sensation scores were obtained following initial donning of the clothing and/or respirator at 10-minute intervals throughout each heat exposure session.

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 completion of 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 40-45% of $\dot{V}O_{2\,max}$. 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 a predetermined endpoint criteria for T_c (39.0^{o}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 climatic chamber and were assisted with removal of the test clothing and/or mask. A final nude 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. 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.

Heart rate and rhythm were monitored continuously throughout heat exposure trials and recorded on-line in five-minute intervals using a telemetry system. The rate of body heat storage for each mask and clothing configuration was calculated using the formula of Craig *et al.*[10]

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 10.0 for Windows. Statistical significance was accepted at the p<0.05 level. Unless otherwise stated, data are presented as means ± SD.

2. NEGATIVE PRESSURE RESPIRATOR TEST (TEST 2)

Four 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: age, 36 ± 3 years; weight, 89.1 ± 1.2 kg; height, 179.9 ± 5.2 cm; maximal oxygen consumption, 2.6 ± 0.3 L · min^{-1}; and trait anxiety, 26 ± 5. A written statement of voluntary consent was obtained from each volunteer before testing began.

Testing procedures for determination of treadmill speeds and grades needed to elicit 40-45% of $\dot{V}O_{2\,max}$ for each subject were identical to those performed in Test 1. Likewise, methods and procedures

utilized for recording thermoregulatory and subjective responses to heat stress were the same. However, the mask condition for Test 2 was the M40A1 negative pressure respirator. In addition, Test 2 involved longer periods of walking (30 min) and did not include the flight simulation task. Heat exposure sessions were still limited to 120-min duration. Statistical analyses of the results were completed independent of the analysis done for Test 1 using the same techniques.

<div align="center">RESULTS</div>

1. TEST 1

Core temperatures were statistically similar between the masked and unmasked coverall conditions at each minute for the entire measurement period. Core temperatures were statistically similar between the masked and unmasked JSLIST conditions at each minute of heat exposure up to 109 min. However, T_c was significantly higher under AERP wear conditions compared to unmasked conditions after 110 min of heat exposure.

Comparisons of T_c between clothing conditions without mask wear (i.e., coveralls vs. JSLIST) indicated that T_c was generally higher under JSLIST conditions for the duration of the heat exposure sessions; however, minute-by-minute averages were not statistically different. Analysis of T_c responses for the two AERP wear conditions showed that T_c was significantly higher for the AERP with JSLIST condition compared to the AERP with coveralls condition from the beginning of the second treadmill walk until the end of the heat exposure period (i.e., 70 min to 120 min) (Figure 1).
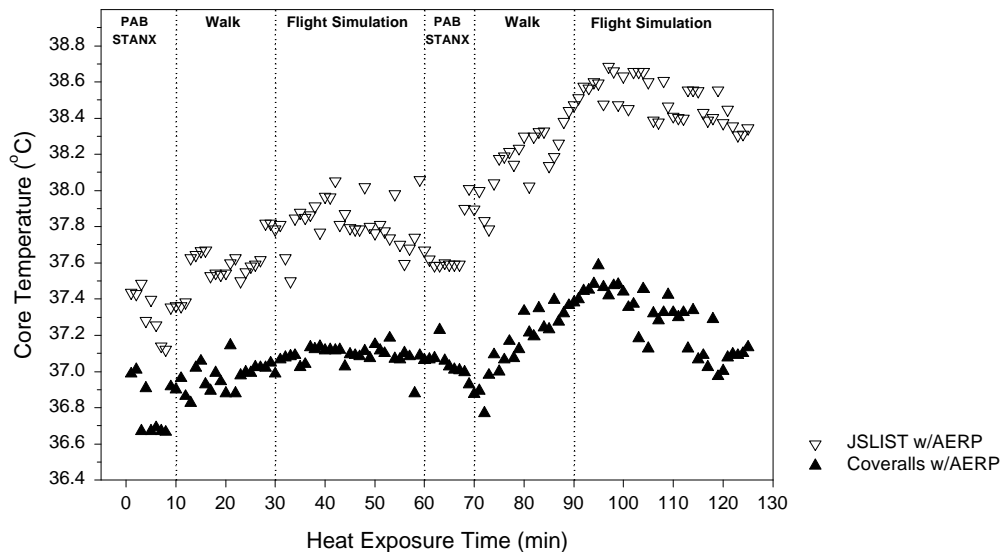

Figure 1. Average T_c responses with and without the JSLIST during wear of the AERP.

Average MWST were statistically similar between the masked and unmasked conditions for both the coverall and JSLIST garments at all measurement periods. MWST were higher for both JSLIST conditions compared to the coverall conditions and the highest MWST were recorded for the AERP with JSLIST configuration. MWST were significantly higher for the AERP with JSLIST condition compared to the AERP with coveralls condition from 95 minutes to the end of heat exposure. Average heart rate

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responses for the masked and unmasked experimental conditions followed a pattern similar to MWST and no differences were found between conditions throughout the heat exposure sessions.

No statistical differences in sweat rates or heat storage rates were found between the masked and unmasked coverall or between the masked and unmasked JSLIST conditions following heat exposure. However, average heat storage rate was significantly greater for the AERP with JSLIST condition (46.9 ± 15.8 kcal· m^{-2}· h^{-1}) compared to the AERP with coveralls condition (15.5 ± 5.8 kcal· m^{-2}· h^{-1}). No interactive effects of experimental condition with the different heat exposure tasks were found on subjective data related to RPE and thermal sensation of the face and body.

2. TEST 2

Core temperatures were statistically similar between the masked and unmasked JSLIST overgarment conditions throughout the entire measurement period. Core temperatures were also similar between the masked and unmasked coverall conditions at each minute for the entire measurement period and did not differ statistically from the beginning to the end of testing.

Without the M40A1 mask, increases in T_c were similar for the JSLIST and coveralls garments up to 96 minutes of testing (Figure 2). With the exception of the data recorded at 117 minutes ($P = 0.07$), T_c were statistically higher during wear of the JSLIST garment compared to the coveralls for the remainder of the 120-minute heat exposure session. During mask wear, increases in T_c were similar for the JSLIST and coveralls garments up to 101 minutes of testing. Thereafter, T_c values were statistically higher during wear of the JSLIST garment compared to the coveralls.
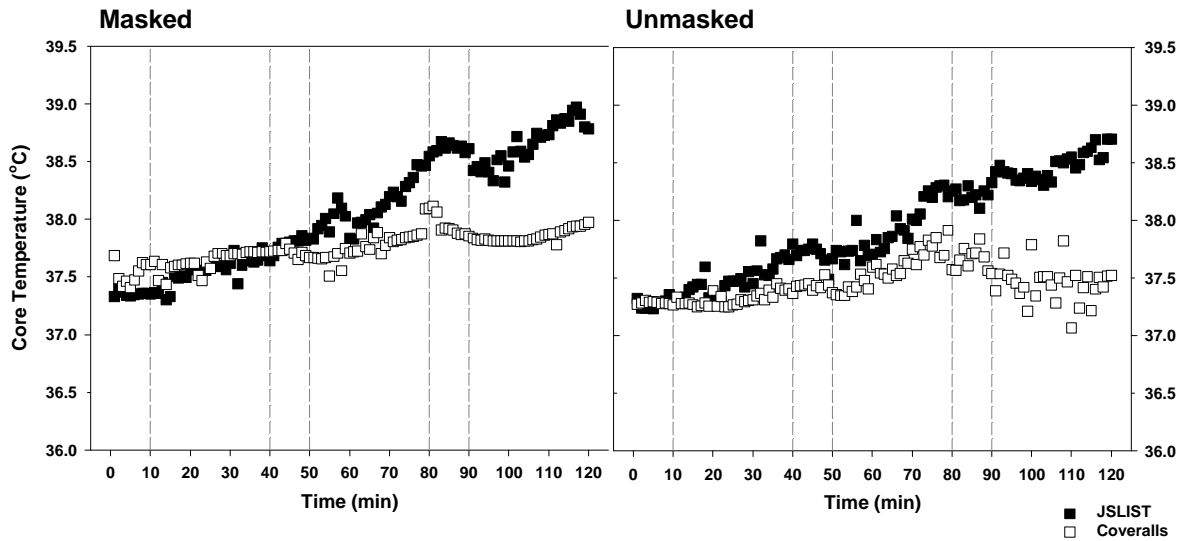

Figure 2. Minute average T_c for masked (M40A1) and unmasked test conditions with and without the JSLIST suit.

For the most part, average heart rate responses were similar between experimental conditions. However, heart rate was significantly lower for the unmasked JSLIST condition compared to the masked JSLIST condition at 110 min (125 ± 6 vs. 156 ± 5 beats· min^{-1}), 115 min (125 ± 4 vs. 156 ± 6 beats· min^{-1}), and 120 min (125 ± 4 vs. 159 ± 4 beats· min^{-1}) of heat exposure. Heart rate tended to be

higher during JSLIST wear compared to conditions of coverall wear for both masked and unmasked conditions, but no significant differences were found.

Average MWST did not differ between any of the masked and unmasked experimental conditions at any time during the 120-min heat exposure tests. However, with the exception of data recorded at 45 min, MWST were significantly higher for the M40A1 JSLIST condition compared to the M40A1 coverall condition between 35 and 100 min of testing. After 100 min, the differences between conditions persisted but did not reach significance. Without the mask, MWST were also significantly higher during JSLIST wear compared to coverall wear after 35 min of testing. Independent of time, average MWST were significantly greater for all JSLIST conditions compared to both conditions of coverall wear.

Sweat rates and heat storage rates did not differ between the masked and unmasked coverall conditions or between the masked and unmasked JSLIST conditions following heat exposure. In addition, no differences were observed between the masked coverall and masked JSLIST conditions or the unmasked coverall and unmasked JSLIST results. Subjective RPE scores and thermal sensation ratings for the face and whole body did not differ between experimental conditions at any time during the test session.

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.[1-3] Likewise, most reports state that heart rates tended to be higher with a mask on. However, we found no statistical differences in sweat rates, heart rates, or MWST between the masked and unmasked coverall conditions of either Test 1 or Test 2. In addition, T_c responses between the unmasked and masked coverall conditions were similar in both tests and total body heat accumulation and heat storage rates did not differ between conditions. Collectively, these findings suggest that there is no measurable thermal load attributable to just a mask in the absence of CP clothing, regardless of mask type.

Masked and unmasked thermoregulatory responses for trials that involved wear of the JSLIST CP overgarment were, for the most part, similar for both Tests 1 and 2. No differences in sweat rates or MWST were found between masked and unmasked conditions with the JSLIST in either test. In Test 1 with the AERP mask, heart rate responses were similar between the unmasked and masked JSLIST conditions. However, in Test 2 with the M40A1 mask, heart rate was significantly lower for the unmasked JSLIST condition compared to the masked JSLIST condition after 110 min of heat exposure. A similar difference in T_c responses was not observed between the unmasked and masked JSLIST conditions. Interestingly, the opposite T_c and heart rate responses were observed between the unmasked and masked JSLIST conditions of Test 1. In brief, average heart rates were identical between conditions and T_c were significantly higher under AERP wear conditions after 110 min of heat exposure. Whether or not these findings indicate that mask wear causes a certain degree of thermal burden in and of itself during wear of CP clothing is difficult to say considering the differing heart rate and T_c responses observed in our tests. However, the limited test sample population sizes of each study highlights the need for additional testing to reach a more definitive conclusion on the thermal load of a mask.

Despite the inconclusive results evident between masked and unmasked JSLIST conditions, the results of both Tests 1 and 2 demonstrated a thermal load effect of the CP clothing ensemble, a finding that has

been reported elsewhere.[4] Wear of the JSLIST resulted in higher T_c, MWST, and heat storage rates compared to the coverall conditions whether or not a mask was worn and the masked JSLIST condition tended to result in the higher values for all thermoregulatory parameters. The differences between T_c and MWST for the coverall and JSLIST conditions were significant for each test, although at different times during heat exposure.

CONCLUSIONS

The thermoregulatory effect of wearing a PAPR or negative pressure respirator without CP clothing appears to be similar to that produced when no respirator is worn. In contrast, differing heart rate and core temperature responses between masked and unmasked conditions suggest that mask wear may cause some degree of additional heat stress when worn in combination with CP overgarments. However, thermoregulatory responses observed for the CP clothing by itself suggest that the protective suit may be the greatest contributor to physiological thermal load during heat exposure. Therefore, designing for a reduced respirator thermal load should not be a significant focus for future mask development efforts.

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