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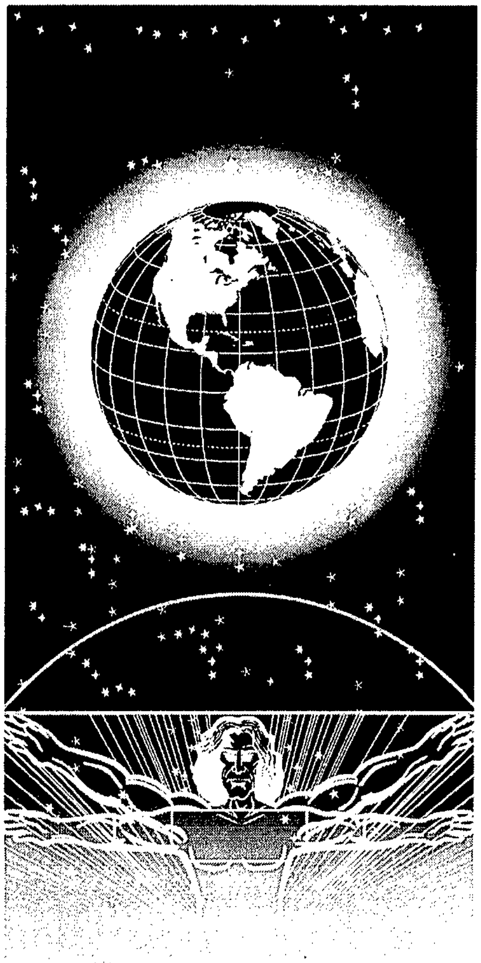

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HEAT STRESS EFFECTS WITH TWO USAF G-PROTECTION SYSTEMS

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This report has been reviewed and is approved for publication.

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14. ABSTRACT
The USAF's Combined Advanced Technology Enhanced Design G-Ensemble (COMBAT EDGE-CE) uses positive pressure breathing (PPB) to enhance acceleration tolerance. A counter-pressure vest is worn to balance intra-thoracic pressure during PPB. Aircrew have reported an increased thermal burden with wear of the CE vest. Thus, this study was designed to compare the heat load of wearing the USAF's standard anti-G system (STD) to that of CE, and to determine if the heat stress had any adverse effect on G-tolerance. Results: Mean weight loss was 1.10 ± 0.24 kg with CE and 1.08 ± 0.28 kg with STD (no significant difference). Maximal rectal temperature was the same for CE and STD (38.1 ± 0.4 °C). Maximal attained relaxed, gradual onset $+G_z$ tolerances after heat stress were 7.1 ± 1.3 for CE and 6.3 ± 0.9 for STD ($p<0.01$). Conclusions: Following heat stress, no significant differences were found between CE and STD with regard to core and skin temperature, or dehydration level. However, use of CE did produce a significantly higher relaxed, gradual onset G-tolerance both before and after heat stress.

15. SUBJECT TERMS
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SUMMARY

Background: The USAF's Combined Advanced Technology Enhanced Design G-Ensemble (COMBAT EDGE) uses positive pressure breathing (PPB) to enhance acceleration tolerance. A counter-pressure vest is worn to balance intra-thoracic pressure during PPB. Aircrew have reported an increased thermal burden with wear of the COMBAT EDGE (CE) vest. Thus, this study was designed to compare the heat load of wearing the USAF's standard anti-G system (STD), which does not require a vest, to that of CE, and to determine if the heat stress had any adverse effect on G-tolerance. **Methods:** Twelve subjects (6 aircrew) participated. Thermal stress (20 min walking at 35 ±0.2°C, radiant heat and 85±1% relative humidity and wind speed 1 m/s) was followed by normalization to 21 °C. Body weight, core and skin temperatures, blood parameters, and G-tolerance were assessed before and after heat stress. **Results:** Mean weight loss was 1.10±0.24 kg with CE and 1.08±0.28 kg with STD (no significant difference). Maximal rectal temperature was the same for CE and STD (38.1±0.4 °C). Differences in maximum skin temperature at the chest and back were not significant. Maximal attained relaxed G load (+G_z gradual onset) after heat stress was 7.1±1.3 for CE and 6.3±0.9 for STD ($p<0.01$). With the exception of osmolality (CE slightly higher), no differences in hemoglobin, hematocrit, or electrolytes were found between CE and STD gear after heat load. **Conclusions:** Following heat stress, no significant differences were found between CE and STD with regard to core and skin temperature elevation, or dehydration level. However, use of CE did produce a significantly higher relaxed, gradual onset G-tolerance.

BACKGROUND

Perceived thermal loads by USAF pilots wearing the Combined Advanced Technology Enhanced Design G Ensemble (COMBAT EDGE) counter-pressure vest on hot and humid days were the origin of this study. COMBAT EDGE (CE) is used in F-16 and F-15 fighter aircraft to increase aircrew G-endurance at high $+G_z$ loads. CE administers positive pressure breathing during G (PBG) with a linear pressure increase from zero pressure at $+4\ G_z$ to 60 mm Hg (8 kPa) at $+9\ G_z$, and utilizes a counter-pressure vest to balance the intra-thoracic pressure.

Thermal burden is a concern for aircrew for a number of reasons, one being its potential effect on G-tolerance. Nunneley and Stribley (11) demonstrated that a dehydration level of 1 - 3% of the body weight was sufficient to reduce G tolerance. However, Balldin and Siegborn (1) showed that thermally dehydrated aircrew appeared to have longer endurance times during straining maneuvers with pressure breathing than without, but the improvements were not statistically significant. From this one might conclude that if crews are suffering from heat stress and dehydration, they may still perform better with a PBG system such as CE, or at least, not have reduced G-endurance times.

Nunneley and Vanderbeek (9) examined whether CE created a greater perceived heat load than standard summer flight gear (STD) during F-16 sorties in hot weather. The study showed that while the crews thought they were hotter with CE, core temperatures with and without CE were not statistically different. However, the authors stated that the failure to demonstrate objective differences may have been due to the variability of conditions inherent in field studies.

Thus, to address the war-fighters' concern that CE is hotter than standard flight equipment, it was necessary to compare the thermal burden from the two equipment conditions in a controlled laboratory environment. This study was designed to measure that thermal load and any subsequent effect on G-tolerance.

METHODS

Experiments were conducted in the Air Force Research Laboratory human centrifuge and thermal chamber at the Biodynamics and Protection Division at Brooks Air Force Base, Texas. The thermal chamber was equipped with a treadmill to simulate aircrew preflight workload, an ejection seat mock-up, and instrumentation for physiologic measurements.

Twelve volunteers (two females and 10 males) served as subjects for this study. The subjects ranged in age from 22-48 years (mean age 32 years, SD ±7). Their mean height was 178 ±8 cm and mean weight 84 ±18 kg. Six of the volunteers were members of the laboratory's acceleration subject panel and six were rated aircrew currently flying F-16 or F-15 aircraft. The subjects were not specifically acclimatized to heat as the study was done in the late winter and spring in Texas. The voluntary, fully informed consent of the subjects used in this research was obtained as required by 32 CFR 219 and was in accordance with AFI 40-402. Each subject was required to complete two experimental conditions conducted on separate days with at least 44 hours between tests. The order of conditions was balanced, so that half started with CE and the other half started with STD flight equipment. Each subject also participated in a two-hour training session, held at least one day prior to his/her first test day. The training session involved centrifuge familiarization rides and orientation to and training for a target-tracking task both at +1 G_z and up to +5 G_z. Subject's activity, food, and fluid intake the day prior to each test was *ad libitum* with the exception of alcohol, which was prohibited.

Before each test, the subject's nude weight (bladder empty) was recorded. Venous blood samples (a maximum of 20 ml from an antecubital or hand vein) were drawn for pre-experiment hemoglobin (Hb), hematocrit (Hct), and electrolyte chemistry and plasma osmolality determinations. The blood samples were stored in standard 5 ml vacutainers and were transported within 30 min to the clinic at the Air Force Base for analyzes according to standard clinical procedures. Standard sternal and biaxillary EKG electrodes were attached to allow for calculation of heart rate. The subject was then instrumented with thermistors to measure skin temperature at the chest, back and thigh (YSI Series 709 thermistor, Yellow Springs, Ohio, USA) as well as a rectal probe (YSI Series 701) for the temperature at the rectum. Thereafter, the subject dressed in one of the two sets of aircrew clothing that represented the two experimental conditions. The clothing sets consisted of either STD or CE equipment. Since each equipment condition consisted of several different layers of clothing and other protective gear, the thermal insulation and evaporative resistance of each equipment set was not known. The individual items worn in each clothing set were as follows:

a. Standard Flight Equipment (STD): HGU-55/P Helmet, MBU-20/P Oxygen Mask, CSU-13B/P Anti-G Suit, PCU-15A/P or PCU-16 A/P Parachute Harness with LPU-9/P Life Preserver, SRU-21/P Survival Vest, CRU-94/P Connector Block, CWU-27/P Aircrew Coverall (flight suit), GS-FRP-2 Flight Gloves, and Flight Boots.

b. COMBAT EDGE (CE): the same as above plus a CSU-17/P Counter-pressure Vest

The weight of the subject with full flight equipment was measured before the subject proceeded to the centrifuge (configured for an F-15 seat back angle of 13°) for a baseline G-tolerance assessment prior to the thermal stress exposure. Part of the baseline measurement included the target-tracking task, which was displayed on a computer screen mounted in the centrifuge gondola. The task display screen resembled an F-16 head up display. The methodology to incorporate the tracking task into the centrifuge control system utilized the state vector of the simulator to generate a chase target for the subject to bring into his gun-sights. The methodology enables a predetermined G-Time vector to be presented as the subject's goal.

The following G-profiles were used to estimate relaxed gradual and rapid onset tolerances:

a. A relaxed, gradual onset (0.1 G/s) run (GOR), to the onset of visual symptoms or +9 G_z. For all relaxed runs, the subject was instructed to not perform any anti-G straining maneuver or other form of muscular contraction. However, the subject's G-suit was inflated according to its normal pressurization schedule. When subjects wore CE equipment, positive pressure was applied to the airways and counter-pressure to the thorax according to the pressure schedule described earlier. For all G-profiles, end point criteria were subject reported 100% loss of peripheral vision and/or 50% loss of central vision as determined by peripheral lights at a 60° angle from centerline and a central light.

b. After a 5 min rest period, an attempt at a series of relaxed rapid onset (6.0 G/s) runs (ROR) to +3 G_z, +4 G_z, +5 G_z, +6 G_z, +7 G_z, +8 G_z and +9 G_z. Each G-exposure lasted for 15 s or until vision end point criteria were reached. If end point criteria were reached, the immediate lower G-level was recorded as the subject's relaxed rapid onset tolerance and subsequent G levels were not attempted. The subject had a 2-min rest period between exposures. After each ROR, the subject provided an estimate of his/her overall stress level during the G exposure by using the following stress level scale with units from 0 to maximal 11 (modified from the Borg scale (3) developed for perceived exertion):

0	**Nothing at all**
0.5	**Very,very weak (just noticeable)**
1	**Very weak**
2	**Weak (light)**
3	**Moderate**
4	**Somewhat strong**
5	**Strong**
6	
7	**Very strong**
8	
9	
10	**Very, very strong (almost max)**
11	**Maximal**

The same scale was also used for evaluation of the thermal stress, although it was not specifically validated for its use to estimate thermal sensation, and should, therefore, only give a rough estimate of the perceived heat stress.

After the centrifuge runs, the subject walked to an adjacent building and entered the thermal chamber. The chamber was pre-heated to and kept at a dry bulb temperature (Tdb) of 35 ±0.2 °C and a relative humidity level of 85 ±1 %. The thermal chamber fans created a wind speed around the subject of 1 m/s. These temperature and humidity conditions were selected to simulate a hot day at a typical Air Combat Command Air Force Base location in the Southeastern US. The subject stood at rest on a level treadmill for 5 min while instrumentation was connected. After the instrumentation period, sixteen 375 W infrared heat lamps in the ceiling (distance to the subject's head varying from about 1 to 2 m) were turned on creating a black globe temperature of 50 ±2 °C. The subject then started walking on the treadmill at 4 km/hr for 20 min without helmet or oxygen mask to simulate walking to the aircraft and conducting a preflight inspection. After the 20-min walking period, the heat lamps were switched off.

Still in the climatic chamber, the subject then spent five minutes strapping into an ejection seat mock-up located next to the treadmill, donning his/her helmet and mask, and connecting the oxygen hose to an A-14 breathing regulator. Over the next 20 min, chamber Tdb was lowered linearly to 21 °C with low humidity (about 40 % relative humidity in room air) to produce conditions expected in flight.

Total time in the climatic chamber was 50 minutes. Every 5th min the subject indicated his/her subjective heat stress level on a scale from 0 to 11 (see scale above). The thermal exposure (as well as the experiment) was to be discontinued early on any one of the following indications: (a) subject request, (b) medical monitor or investigator request, (c) physiological measurements exceeding any one of the following: heart rate > 85% of estimated maximum (220-age); rectal temperature $\geq$ 39.0 °C; skin temperature (any site) > 43 °C. The heart rate data in the thermal chamber were only used for monitoring the subject's physiological condition for safety reasons.

After the thermal exposure, the subject returned to the centrifuge and followed the required strap-in procedures. During the following 15-min period, he/she was exposed to three trials of closed loop G-exposure, with a 5-min rest period between trials. Closed loop signifies the subject regulated the G-level using the control stick of the target-tracking task. Data on target tracking performance were gathered during each trial. The target G-levels were reached with a maximum 6 G/s onset rate. For each closed loop trial, the G-profile consisted of a 5s exposure to +5 G_z, followed by 5s at +4 G_z, then 10s at +1.5 G_z, with this sequence repeated four times. When all of the closed loop trials were completed, the subject had a 10-min rest period during which he/she repeated the target-tracking task three times.

After the 10-min rest period, post-thermal exposure measurements of relaxed gradual and relaxed rapid onset G-tolerances were conducted, according to the same procedures as described above. Additionally, straining ROR exposures (15 s each) followed after a 5-min rest. For straining exposures, the subjects were instructed to perform a normal anti-G straining maneuver to help maintain full vision. Each subject began his/her straining RORs at the same G-level as he/she failed during the relaxed ROR runs, followed by higher G-levels up to a maximum of +9 G, if the end point criteria were not reached.. The maximal G-level was confirmed in the same way as done with the relaxed ROR exposures. The subject estimated his/her stress level during each G-exposure using the 0 to 11 scale.

After the centrifuge exposures, the subject's weight with all clothing and equipment (for an estimate of evaporation when comparing it to the weight before the thermal and centrifuge exposures) and later the nude weight (before emptying the bladder) were again measured and post exposure venous blood samples (20 ml) were drawn for Hb, Hct, electrolyte chemistry and osmolality determinations.

Statistical analysis: The skin and core temperature data, body weights, blood sample data, tracking task scores, G-levels reached and time at G, and heart rates were analyzed with Statistical Analysis Software (SAS). Since the sample size was small, both parametric and non-parametric tests (Student's t-test and Wilcoxon Signed Rank Test, respectively) were used to cross check findings. In all cases, the results were compatible. The assumption of normality of the data was checked. The data from subjective ratings were not within the normal distribution and did not lend themselves to statistical analysis; consequently, the results are reported only as raw data.

RESULTS

Body temperatures and subjective heat stress

The rectal temperature rose in 11 subjects (core temperature data was not available for one subject) by a mean of 0.9 °C with both CE and STD equipment. The mean maximal rectal temperature with CE and STD was also the same, 38.1 °C (SD ±0.4). Consequently, there was no significant statistical difference (n.s.) between the two equipment conditions. For both sets of equipment, the peak of the mean rectal temperature occurred approximately midway through the 20 minute cool down period in the climatic chamber (see Fig 1 and 2). Mean rectal temperatures for CE and STD were still elevated above pre-test values, 0.5 °C and 0.4 °C, respectively, at the end of the test period, which was approximately 75 minutes after the climatic chamber exposure.

The maximal subjective rating of heat stress was a mean of 3.6 units (±2.4) with CE and 3.9 units (±2.9) with STD. Figures 1 and 2 show that while mean rectal temperature continued to climb after the start of the cooling of the climatic chamber, the subjects' perceived heat stress had already begun to decrease by that point.

The mean chest skin temperature rose to 38.2 °C (±0.8) with CE and to 38.0 °C (±0.4) with STD, the back skin temperature rose to a mean of 38.5 °C (±0.8) with CE and to 38.4 °C (±0.5) with STD , and the thigh skin temperature rose to a mean of 38.3 °C (±0.6) with CE and to 38.3 °C (±0.5) with STD. None of the differences in skin temperature were statistically significant. Figures 3 and 4 show the chest and back skin temperatures for CE and STD, respectively. Unlike with rectal temperature, the mean subjective rating of heat stress followed the pattern of both chest and back skin temperature for CE and STD.

Weight loss

The mean weight loss for all 12 subjects was 1.10 kg (±0.24) with CE and 1.08 kg (±0.28)with STD (difference n.s.), corresponding to a mean weight loss of 1.3 % (±0.2) of the body weight for both conditions. As an indication of the evaporation from the flight equipment, the subject's weight was measured with full equipment before and after the thermal and centrifuge exposures. The mean weight loss with full equipment was 0.53 kg ±0.16 with CE and 0.59 kg ±0.12 with STD, with no statistically significant difference between the two conditions.

Results of the blood samples

Hemoglobin concentration increased from a mean of 15.2 g-dL^{-1} ±1.1 before heat stress to 15.7 G/DL ±0.9 after ($p < 0.01$) with CE, and from 15.2 G/DL ±0.9 to 15.6 g-dL^{-1} ±0.9, respectively, with STD ($p<0.01$). The mean difference in hemoglobin concentration between CE and STD equipment after the heat stress was not statistically significant. Hematocrit was 45.8 % ±2.9 before heat stress and 46.7 % ±2.2 after with CE (n.s.), and increased from 45.6 % ±2.5 to 46.3 % ±2.4, respectively, with STD ($p<0.05$). The mean difference in hematocrit between CE and STD equipment after the heat stress was not statistically significant. The osmolality increased from 290 mosm.kg^{-1} ±5 before heat stress to 294 mosm.kg^{-1} ±5 after ($p<0.05$) with CE, and increased from 289 mosm.kg^{-1} ± 8 to 291 mosm.kg^{-1} ± 5, respectively, with STD (n.s.). The difference in osmolality between CE and STD equipment was statistically significant ($p<0.001$). The mean sodium values after heat stress were 141 meq.L^{-1} (±2) with CE and 140 (±2) with STD (n.s.). The mean potassium values after heat stress were 4.2 meq.L^{-1} (±0.3) with CE and 4.2 (±0.3) with STD (n.s.). The mean chloride values after heat stress were 99 meq.L^{-1} (±4) with CE and 98 (±3) with STD (n.s.).

Using hematocrit and hemoglobin values, the percentage changes in volumes of blood, plasma, and red cells in dehydration could be calculated according to Dill and Costill (5). The changes in blood volume after heat stress were calculated to –2.5% with CE and –2.6% with STD. The corresponding changes in red cell volume were –1.7% for CE and –1.1% for STD and the changes in plasma volume were –3.2% and –3.9%, respectively.

G-tolerances before and after heat stress with the different equipment

The mean maximal G-level attained with CE during relaxed gradual onset run (GOR) G-exposures decreased from 7.6 G ±1.3 before heat stress to 7.1 G ±1.3 after ($p<0.05$). With STD, GOR performance decreased from 7.1 G ±0.8 before heat stress to 6.3 G ±0.9 after ($p<0.001$). The mean maximal, relaxed rapid onset run (ROR) time with CE was 56 s ±19 before heat stress and 49 s ±24 after ($p<0.05$). With STD, the times were 55 s ±16 and 48 s ± 20, respectively, ($p<0.01$). Time was determined by summation of the total seconds a subject was exposed to G. ROR exposures began at +3 G and lasted a maximum of 15 s at each G level. Consequently, a time of 49 s would signify the subject completed runs at +3, +4, and +5 G, but stopped at the 4 s point during the +6 G exposure.

The post thermal G-levels reached during the relaxed GOR exposures with CE and STD, 7.1 G (±1.3) and 6.3 G (±0.9), respectively, were significantly different ($p<0.01$). There was no significant difference between the mean maximal, relaxed ROR times: 49 s (±23) with CE and 48 s (±20) with STD. Similarly, there was no significant difference for the rapid onset G-exposures with use of straining maneuvers. The mean added time at high G was 42 s (±28) with CE and 41 s (±20) with STD. "Added time" represented the G-exposures the subjects could complete beginning at the G level they failed to complete during relaxed ROR runs. The mean maximal reported stress level during the straining exposures was lower with CE (5.8 units (±2.2)) than with STD (6.6 units (±2.5)).

Heart rates during the G-exposures after heat stress with the different equipment

The heart rates were compared between CE and STD during the G-exposures after the heat stress. For the relaxed GOR exposures, the heart rate values given for each subject represent those at the maximum G-level the subject could attain with both equipment conditions (CE and STD). Thus, the mean maximal heart rate for all subjects during gradual onset runs was 114 bpm (±14) with CE and 111 bpm (±15) with STD (n.s). The mean maximal heart rate at the highest relaxed, rapid onset G-level that could be attained for 15 s during both conditions by each subject was 110 bpm (±21) with CE and 111 bpm (±19) with STD (n.s.). Calculated in the same way, the mean maximal heart rate during the rapid onset runs using the straining maneuver was 152 bpm (±19) with CE and 146 bpm (±14) with STD (n.s.). During these G-exposures using the straining maneuvers the mean perceived effort level was 5.8 units (±2.2) with CE and 6.6 units (±2.5) with STD.

Performance during the target-tracking task

A comparison of the tracking task performance between CE and STD during closed loop centrifuge exposures and during tests at 1 G, after the heat stress, was made. The mean RMS values during the closed loop centrifuge exposures were 0.78 (±0.23) with CE and 0.80 with STD (n.s.). RMS indicates the root mean square of the G-level error (the lower the RMS value, the better the performance). The mean time on target (TOT) was 69.8 s (±4.8) with CE and 68.9 s (±3.1) with STD (n.s.). TOT means that the aircraft gun sight symbol was congruent with the target airplane symbol (the higher the value, the better the performance). During the 1-G tests after the heat stress, the mean RMS value was 0.58 (±0.17) with CE and 0.60 (±0.20) with STD (n.s.). The mean TOT at 1 G was 73.0 s (±2.2) with CE and 74.5 s (±3.6) with STD (n.s.).

The original data for rectal and skin temperatures, body weight loss, maximal attained relaxed G-levels at GOR, time at G with ROR and added time during straining ROR, heart rates, blood samples, and performance during flight simulation tracking tasks are given in Tables I to VI at the end of the report.

DISCUSSION

The heat stress condition used in this study was chosen following a review of weather data collected at several USAF bases in the southern U.S. over the last few hot seasons. The 20 minutes of heat stress was designed to simulate the thermal exposure for a pilot during the preflight walk-around inspection of the aircraft. During post experiment interviews, the aircrew subjects described the simulation as a good worst-case scenario, best resembling the time and workload encountered when forced to move to a second aircraft during preflight.

Aircrew subjective complaints regarding use of CE versus STD during hot and humid days, which were the origin of this study, were not validated by our objective findings. This was indicated by the similar maximal core temperature (38.1 °C) and similar increase in core temperature (0.9 °C) as revealed by measurements before thermal exposure and at the peak body temperature with the two equipment conditions. Nunneley et. al. (4) also failed to show any statistically significant thermal difference between CE and standard equipment during an in-flight study using F-16 sorties in hot weather. While there was no temperature difference between the two equipment ensembles used in this current study, the mean peak temperature for both exceeded the upper core temperature limit of 38 °C recommended for crew of high-performance aircraft (9, 10).

The maximal skin temperatures for the back, chest and thigh with CE were also not statistically significant when compared to those with standard equipment. If there is an additional heat load for adding the CE counter pressure vest to the aircrew's already multiple layers of clothing and equipment (underwear, flight suit, G-suit, survival vest, and harness with a life preserver unit), it was not reflected in the findings of this study. The subjects actually indicated a somewhat higher subjective heat stress level with the standard equipment than with CE. However, since the heat stress values were very subjective and ranged from 0 (nothing) to 9 (just under very, very high), a minor difference in mean values probably does not have any practical meaning. Both equipment conditions had a different relationship between mean rectal temperature and heat stress scores than between mean skin temperatures and heat stress scores. Figure 1 shows that while mean rectal temperature continued to increase well beyond the end of the treadmill and radiant heat period in the climatic chamber, the subjective heat stress scores (even if the subjective scale is validated only for physical effort level and not for temperature) began to decrease as soon as that period ended. That is in accordance with earlier findings (e.g. ref 8), where an individual's core temperature can be elevated up to one-hour post-heat stress but he/she feels comfortable within a few minutes. The rectal temperature is usually considered a good estimate of the core temperature, as is the esophageal temperature. However, the rectal and esophageal temperatures may have a slightly different course of change during heat or cold stress. The subjective heat stress scores for both CE and standard equipment decreased in the same manner as the chest and back skin temperatures. That is, they rapidly fell when the treadmill and radiant heat were stopped and the chamber temperature began to decrease. It is known that thermal comfort is largely determined by mean skin temperature, as core temperature per se produces no conscious sensation (7).

For both equipment conditions, weight loss corresponded to the sweating of about 1.1 liters, or 1.3% of body weight. A decrease in G-tolerance is usually seen after heat stress and dehydration (1, 11), and that was the case in this study. The maximal attained G-level during relaxed, gradual onset G-exposure decreased after heat stress by approximately 7 % with CE and 11 % with STD. Similarly, an approximate 13 % decrease in time during relaxed, rapid onset G-exposures was seen after the heat stress with both equipment ensembles. This agreed with Nunneley and Stribley's finding that dehydration effects are greater in rapid onset G-exposures (11).

The blood samples were drawn to supplement changes in body weight as a means of detecting any dehydration effects. Measurements of hemoglobin, hematocrit, and electrolytes did not show any significant difference after heat stress between the two sets of equipment. As no difference in dehydration level was indicated by the weight losses, no difference in other measures of dehydration, such as blood concentration levels, was expected. With both equipment conditions, hemoglobin values increased by a mean of about 3 % after, compared to before, the thermal exposure. The corresponding hematocrit values increased similarly by a mean of about 1.8 %. The similarity of the hemoglobin and hematocrit values to the percentage of body weight loss due to thermal stress indicates that the blood sample test methods used were sensitive enough to be able to detect any differences between the equipment conditions, if any such were to be found. Osmolality was statistically higher with CE (mean 294 mosm.kg^{-1} with CE and 291 with standard), but the difference was very small. Both values were well within the normal range for osmolality, which was 270-310 mosm.kg^{-1} for the clinical chemistry laboratory that completed the tests. Therefore, the physiological significance of CE's minimally higher osmolality value might be questionable.

The relaxed, gradual onset G-exposures after the heat stress and dehydration indicated that G-tolerance was higher with CE than with the standard equipment. This was revealed by the statistically significant higher mean maximal value of 7.1 G with CE compared to 6.3 G with standard gear. This means that the beneficial effect on G-tolerance from pressure breathing during G with CE compared to no pressure breathing with STD is maintained even after heat stress. However, there was no difference in tolerance between the two sets of equipment during the relaxed, rapid onset G-runs. The lack of a difference was probably because the subjects only reached G-levels of about 5 G. Pressure breathing during G started at 4 G, with a linear increase to 60 mm Hg (8 kPa) at 9 G. At 5 G, very little (12 mm Hg or 1.6 kPa) and probably physiologically insignificant amounts of pressure breathing were applied to the airways. Consequently, little or no positive effects of the very low pressure breathing during G would be expected.

During the straining, rapid onset G-exposures, similar benefits of straining were seen with both CE and standard equipment (the added times at high G were 42 and 41 s, respectively). Since pressure breathing during G with CE is usually most beneficial during repeated G-exposures, where fatigue is a factor (4), the G-exposures used in this study probably were too short and too few to show any substantial improvement with CE compared to standard equipment. However, the subjective rating of stress was somewhat lower with CE compared to standard (mean 5.8 units vs. 6.6, corresponding to a decrease of about 14 %), which may indicate a positive effect of CE during high G, even after heat stress and dehydration. Similar findings were found in earlier work, where G-tolerance after heat stress was studied with and without pressure breathing during G (1, 12).

The heart rate at the maximal G-level that could be tolerated for both conditions during relaxed, gradual onset runs indicated a tendency to a higher (but statistically not significant) mean value with CE compared to standard. Positive pressure breathing may induce a moderately higher heart rate with high breathing pressures (2), but as the airway pressure only increased moderately at the G-levels reached with relaxed, gradual onset runs, this tendency was not pronounced. During the relaxed, rapid onset G-exposures no differences in heart rate were seen between the two equipment conditions, probably also due to the very low airway pressures at the maximal attained G-level with CE. During the straining, rapid onset G-exposures the higher mean heart rate with CE compared to standard was not significant, probably due to the short G-exposures.

No significant differences in target tracking performance scores were found during the closed loop centrifuge exposures up to +5 G_z or during the tests at 1 G, following heat exposure with CE and STD. Even though the subjects were trained in the tracking task prior to the experiment and also had to execute the test before the thermal exposure, a training effect could not be excluded. However, half of the subjects were aircrew (5 were F-15 or F-16 pilots) and one of the centrifuge panel subjects had about 1000 hours of other F-16 flight simulation experience, all of which should be beneficial when using the target tracking task. Also, 50 % of the subjects started with CE and 50 % started with standard, which should balance out some of the effects of training when comparing the two sets of equipment. This means that operational performance, as estimated with this tracking task, was the same with both equipment conditions, even if a somewhat lower G-tolerance could be seen in some measurements of relaxed, gradual onset G with standard gear compared to CE. As described above, the CE system utilizes very little pressure breathing at +5 G_z. Consequently, at that G level, it functions very similar to the standard equipment and no difference in performance task scores between the two would be expected. However, as pointed out by Maidment (6), "in the cockpit, anything which produces thermal discomfort may be sufficiently distracting to impair performance, even in the absence of physiological heat strain."

CONCLUSIONS

Thermal burden, as measured by body core and skin temperatures and dehydration, was the same for CE as for standard flight equipment (thermal conditions included radiant heat, ambient temperature of 35 °C, and relative humidity of 85 %). With use of CE or standard equipment, G-tolerance was lower following thermal exposure. CE created somewhat better relaxed, gradual onset G-tolerances, and lower subjective stress ratings during straining, rapid onset G-exposures compared to standard equipment, but target tracking performance measures were not statistically different.

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LEGENDS TO TABLES

Table I. The maximal rectal temperature, temperature difference between before and after heat exposure, maximal chest and back skin temperatures, and the subjective rating of heat stress with COMBAT EDGE (CE) and standard equipment (std). # - rectal temperature data was not available for one subject. S.D. – denotes standard deviation. No statistically significant differences (n.s.) between CE and std. Subjects 7-12 were aircrew.

Table II. The body weight loss caused by sweating and the percentage weight loss of the initial body weight with COMBAT EDGE (CE) and standard equipment (std). No statistically significant differences (n.s.) between CE and std.

Table III. Maximal attained relaxed G-level with gradual onset G-exposure (GOR), maximal time at increased G-levels with relaxed, rapid onset G-exposures (ROR), added time at increased G-level with straining, rapid onset G-exposures, and the maximal subjective stress levels during the straining RORs with COMBAT EDGE (CE) and standard equipment (std), respectively. All measurements were made after the thermal exposures. Statistical difference levels are given in the last row (n.s. = no statistically significant difference).

Table IV. The heart rate (HR) in beats per minute at the highest G-level that could be maintained with both COMBAT EDGE (CE) and standard equipment (std) during relaxed, gradual onset runs (GOR), and relaxed and straining rapid onset runs (ROR) after the heat stress. No statistically significant differences (n.s.) were found between CE and std.

Table V. The results of the blood samples after the thermal exposures with COMBAT EDGE (CE) and standard equipment (std). The results of hemoglobin (HGB) are given in G/DL, hematocrit (HCT) in %, sodium, potassium and chloride in MEQ/L, and osmolality in MOSM/kg. # indicates a missing value. The statistical significance levels are given in the last row (no significance = n.s.).

Table VI. The results of the performance during the flight simulation tracking task during closed loop control of the centrifuge and at 1 G with the centrifuge stopped, with COMBAT EDGE (CE) and standard equipment (std), respectively. RMS indicates the root mean square of the G-level error (the lower the value, the better the performance). Time on target means that the aircraft gun sight symbol is congruent with the target airplane symbol (the higher the value, the better the performance). # indicates a missing value. No statistically significant difference levels were found between CE and std (n.s.). Subjects 7-12 were aircrew (7-11 were F-15 or F-16 pilots) and subject 3 had about 1000 hours of other F-16 flight simulation experience.

Table I.

SUBJECT	Max rectal temp °C	Max rectal temp °C	Temp diff °C	Temp diff °C	Max chest temp °C	Max chest temp °C	Max back temp °C	Max back temp °C	Subjective Heat stress	Subjective heat stress
	CE	std	CE	std	CE	std	CE	std	CE	std
1	38.1	38.3	0.9	1.1	37.4	37.6	37.9	38.2	5	9
2	#	38.5	#	1.2	40.6	38.4	38.6	38.3	0	0
3	38.5	37.8	1.1	0.6	38.5	38.1	38.2	38.4	3	4
4	38.1	38.5	0.7	0.9	37.9	38.1	38.6	38.1	5	4
5	37.4	37.5	0.7	0.6	37.5	37.5	37.5	37.5	4	4
6	38.9	38.7	1.0	1.5	38.6	38.8	38.9	39.4	5	4
7	38.1	38.0	0.8	0.6	38.1	37.8	37.8	38.0	4	4
8	38.2	38.3	0.9	0.9	38.1	38.2	39.4	39.2	3	5
9	38.5	38.0	1.2	1.0	38.5	38.0	40.3	38.6	9	9
10	37.9	37.8	1.0	1.2	38.1	37.8	38.4	38.2	3	2
11	37.8	37.7	0.9	1.1	37.8	38.1	38.4	38.2	2	2
12	38.1	38.3	0.6	0.9	37.8	38.1	38.2	38.1	0	0
Mean	38.1	38.1	0.9	0.9	38.2	38.0	38.5	38.4	3.6	3.9
S.D.	0.4	0.4	0.2	0.3	0.8	0.4	0.8	0.5	2.4	2.9
Stat. sign.		n.s.		n.s.		n.s.		n.s.		(+8%)

Table II.

SUBJECT	Weight loss (kg)	Weight loss (kg)	% weight loss	% weight loss
	CE	std	CE	std
1	0.86	0.85	1.0	1.0
2	0.96	0.97	1.3	1.3
3	1.38	1.33	1.4	1.3
4	0.73	0.84	1.3	1.5
5	1.02	1.01	1.4	1.4
6	1.40	1.37	1.7	1.7
7	1.54	1.72	1.3	1.4
8	1.27	1.20	1.2	1.1
9	0.98	0.76	1.3	1.0
10	1.12	1.09	1.2	1.2
11	1.01	0.84	1.2	1.0
12	0.95	1.01	1.6	1.6
Mean	1.10	1.08	1.3	1.3
S.D.	0.24	0.28	0.2	0.2
Stat.sign.		n.s.		n.s.

Table III.

SUBJECT	Max G, GOR, relaxed	Max G, GOR, relaxed	Max time (s) at G, ROR, relaxed	Max time (s) at G, ROR, relaxed	Added time (s) at G, ROR straining	Added time (s) at G, ROR straining	Max subj. stress, ROR, straining	Max subj. stress, ROR, straining
	CE	std	CE	std	CE	std	CE	std
1	7.2	6.9	82	67	4	32	8	10
2	6.5	5.1	39	30	61	45	1	3
3	8.3	7.2	85	94	20	11	3	3
4	8.4	6.0	80	50	3	30	7	9
5	9.0	6.6	64	65	41	40	6	6.5
6	6.5	6.3	38	37	67	68	7	7
7	7.0	7.0	37.5	45	13.5	7	3	4
8	7.8	7.4	19	50	78	46	7	7
9	7.8	7.0	53	45	48	54	8	5
10	4.9	4.8	45	36	20	28	6	8
11	4.8	5.4	21	30	69	67	7	10
12	6.5	5.9	25	21	74	63	6	7
Mean	7.1	6.3	49	48	42	41	5.8	6.6
S.D.	1.3	0.9	23	20	28	20	2.2	2.5
Stat. sign.	p<0.01		n.s.		n.s.		(+14 %)	

Table IV.

SUBJECT	HR GOR, relaxed	HR GOR, relaxed	HR ROR, relaxed	HR ROR, Relaxed	HR ROR, straining	HR ROR, straining
	CE	std	CE	std	CE	std
1	125	125	120	144	175	138
2	95	122	93	110	133	146
3	102	100	141	125	154	144
4	115	95	101	112	140	132
5	110	111	112	108	155	154
6	155	130	150	136	187	182
7	112	129	120	117	124	135
8	131	110	97	92	155	135
9	134	125	122	118	167	145
10	90	90	95	100	150	160
11	100	95	87	85	150	150
12	93	100	82	84	128	135
Mean	114	111	110	111	152	146
S.D.	20	15	21	19	19	14
Stat. sign.	n.s.		n.s.		n.s.	

Table V.

SUB-JECT	HGB	HGB	HCT	HCT	Sodium	Sodium	Potass-ium	Potass-ium	Chloride	Chloride	Osmolality	Osmolality
	CE	std	CE	std	CE	std	CE	Std	CE	std	CE	std
1	16.0	16.8	47.8	48.9	140	142	3.7	4.0	101	102	292	#
2	14.8	15.5	43.4	45.7	143	142	4.2	4.1	99	98	295	294
3	15.9	16.6	48.6	49.4	141	138	4.1	4.4	96	95	291	287
4	14.7	14.1	44.4	42.1	138	137	4.6	4.8	95	96	290	286
5	15.7	15.8	46.3	47.2	142	142	3.8	4.3	98	97	290	289
6	17.8	16.6	50.0	48.1	140	140	3.9	3.8	97	96	293	293
7	15.8	16.2	46.8	48.0	142	142	4.4	4.5	102	102	303	301
8	15.1	15.1	44.8	45.1	144	142	4.5	4.3	108	104	301	294
9	16.0	15.3	47.6	46.2	141	141	4.2	4.0	96	96	290	288
10	16.1	15.9	47.0	47.2	142	140	4.0	3.9	97	96	294	287
11	16.3	15.2	49.5	46.5	137	137	4.4	4.3	99	99	291	285
12	14.7	14	43.9	41.6	142	142	4.4	4.0	98	99	298	295
Mean	15.7	15.6	46.7	46.3	141	140	4.2	4.2	99	98	294	291
S.D.	0.9	0.9	2.2	2.4	2	2	0.3	0.3	4	3	4	5
Stat.sign	n.s.		n.s.		n.s.		n.s.		n.s.		P<0.001	

Table VI.

SUBJECT	RMS closed loop	RMS closed loop	Time on target closed loop	Time on target closed loop	RMS 1G	RMS 1G	Time on target at 1G	Time on target at 1G
	CE	std	CE	std	CE	std	CE	std
1	0.67	0.77	71.60	69.51	0.66	0.57	73.64	73.33
2	0.75	0.90	79.26	72.12	0.46	0.82	73.11	70.66
3	0.69	0.70	73.01	71.20	0.53	0.44	73.56	75.56
4	0.96	1.01	65.23	67.46	0.71	0.96	70.68	67.40
5	0.90	0.95	59.83	63.69	0.63	0.72	74.42	78.75
6	1.21	1.06	65.78	66.28	0.78	0.78	68.63	72.08
7	0.84	0.75	72.42	70.38	0.59	0.56	72.48	73.64
8	0.43	0.52	73.68	72.45	0.32	0.34	75.12	74.75
9	0.51	#	73.92	#	0.33	0.33	75.83	75.72
10	0.75	0.71	74.50	72.48	0.73	0.65	72.93	79.96
11	0.67	0.53	70.30	66.61	0.46	0.48	74.21	74.75
12	0.85	0.95	69.64	69.25	0.73	0.77	72.10	72.01
Mean	0.78	0.80	69.83	68.87	0.58	0.60	73.00	74.46
S.D.	0.23	0.20	4.81	3.05	0.17	0.20	2.16	3.56
Stat. Sign.	n.s.		n.s.		n.s.		n.s.	

LEGENDS TO FIGURES

Figure 1. Mean core temperature (°C) and subjective heat scores during the thermal exposure with COMBAT EDGE equipment.

Figure 2. Mean core temperature (°C) and subjective heat scores during the thermal exposure with standard equipment.

Figure 3. Mean chest and back temperatures (°C) and subjective heat scores during the thermal exposure with COMBAT EDGE equipment.

Figure 4. Mean chest and back temperatures (°C) and subjective heat scores during the thermal exposure with standard equipment.

Figure 1.

Mean Core Temperature and Heat Score

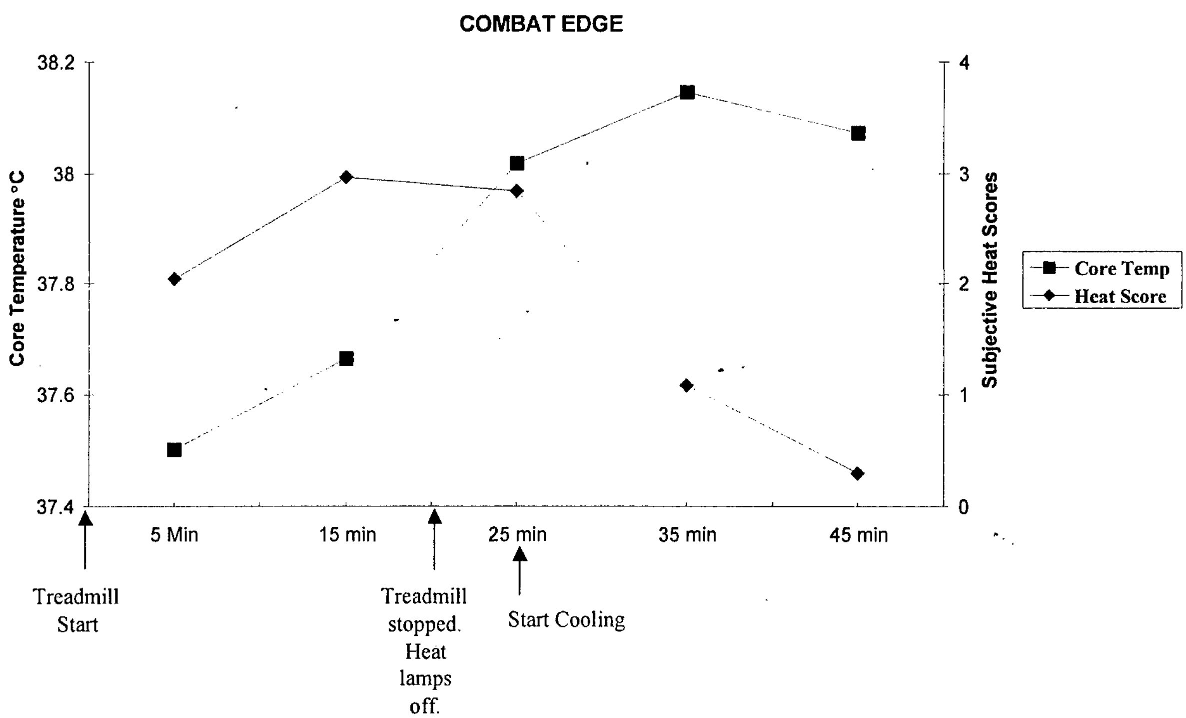


Figure 2.

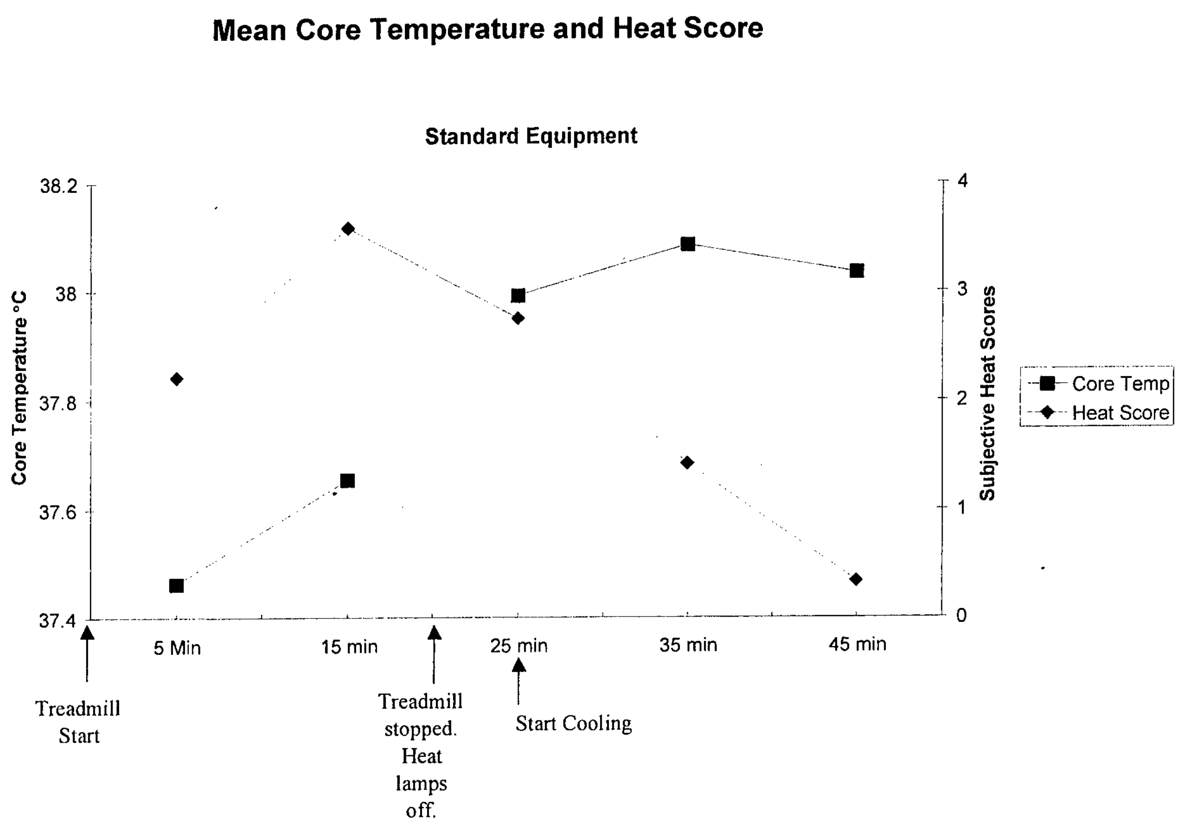
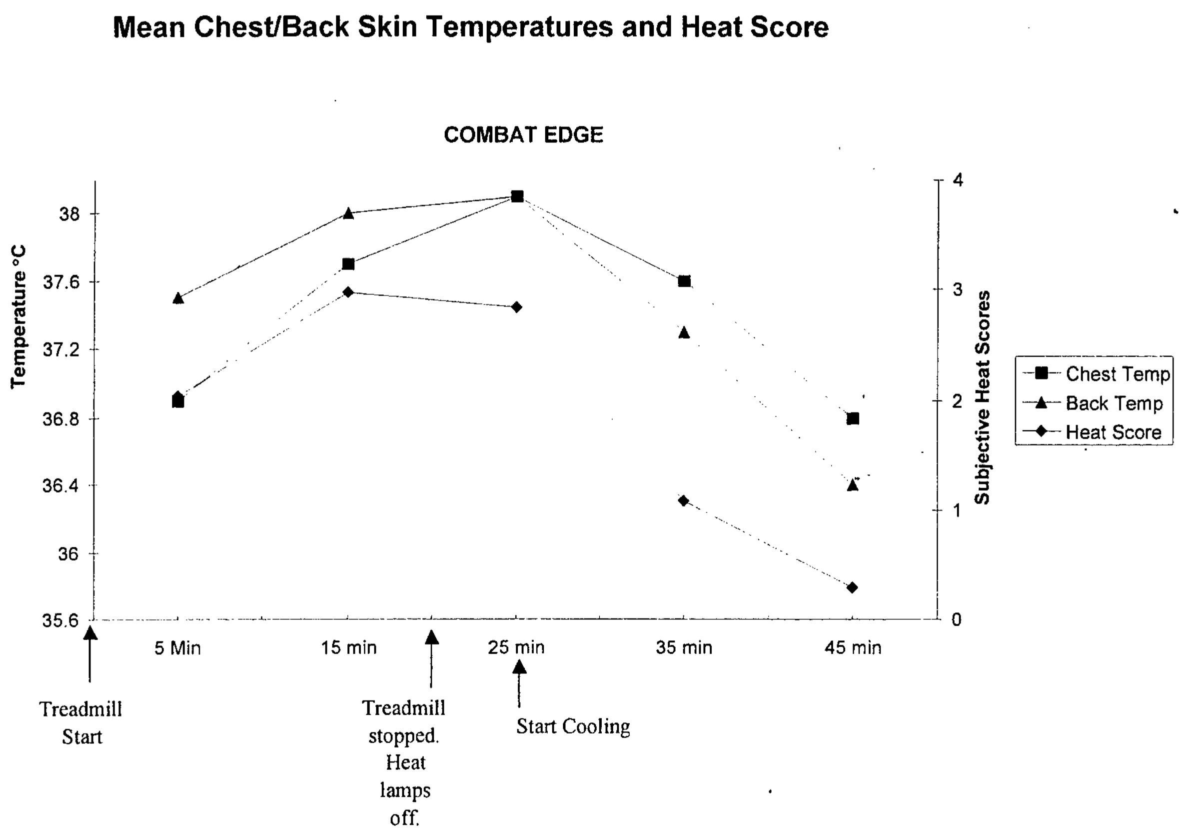
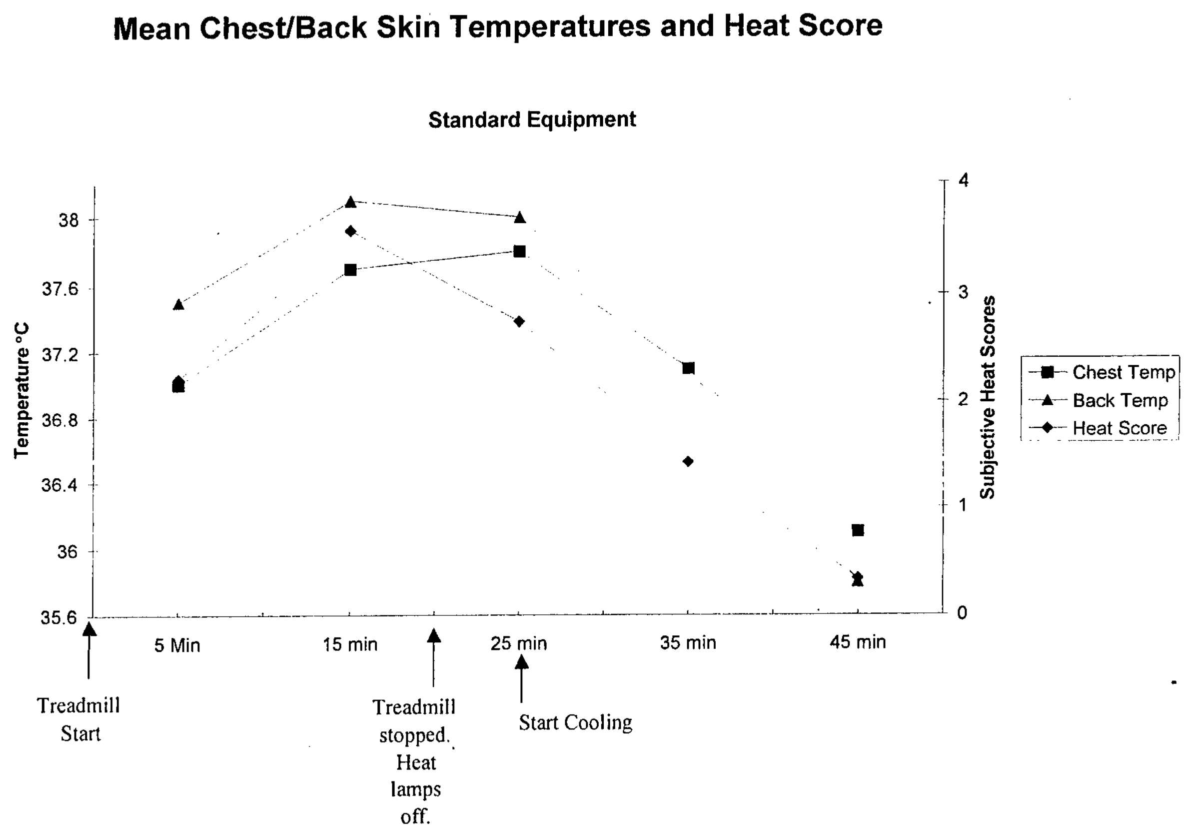

Mean Core Temperature and Heat Score
Standard Equipment
Core Temperature °C
38.2
38
37.8
37.6
37.4
Subjective Heat Scores
4
3
2
1
0
Core Temp
Heat Score
5 Min
15 min
25 min
35 min
45 min
Treadmill Start
Treadmill stopped. Heat lamps off.
Start Cooling

Figure 3.



Mean Chest/Back Skin Temperatures and Heat Score
COMBAT EDGE
Temperature °C
38
37.6
37.2
36.8
36.4
36
35.6
4
3
2
1
0
Subjective Heat Scores
Chest Temp
Back Temp
Heat Score
5 Min
15 min
25 min
35 min
45 min
Treadmill Start
Treadmill stopped. Heat lamps off.
Start Cooling

Figure 4.


Mean Chest/Back Skin Temperatures and Heat Score
Standard Equipment
Temperature °C
38
37.6
37.2
36.8
36.4
36
35.6
5 Min
15 min
25 min
35 min
45 min
Subjective Heat Scores
4
3
2
1
0
Chest Temp
Back Temp
Heat Score
Treadmill Start
Treadmill stopped. Heat lamps off.
Start Cooling