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Head Cooling is Desirable but not Essential for Preventing Heat Strain in Pilots

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Liquid-cooled garments (LCGs) are being considered for reducing heat strain in pilots. While head cooling has been shown to be thermally efficient and subjectively desirable, it is technically difficult to achieve. This laboratory study was carried out to see if head cooling in addition to torso cooling is a necessity. Six male subjects wore a cooling vest and cap under summer flight clothing on three occasions in a climatic chamber set at T_{db} = 42°C, T_{wb} = 32°C (RH = 50%), T_g = 52°C at head position, WBGT = 35°C. Cooling conditions were: control (CTRL), no fluid circulation; condition VEST, only torso cooling; condition HEAD, both torso and head cooling. Cooling fluid was circulated from a reservoir maintained at 10°C. Subjective thermal comfort assessments confirmed the desirability of head cooling, but performance measurements and physiological measurements of thermal strain showed no statistically significant differences between conditions VEST and HEAD. It was concluded that head cooling is desirable but not essential.

MEASUREMENTS OF THE environmental conditions in cockpits have shown that temperatures as high as T_{db} = 40–50°C and T_g = 50–60°C can occur (6,8,13,15,17). The worst conditions arise in aircraft that have been heat soaked with a closed canopy, during taxi and standby, during early flight before onboard air conditioning becomes effective, and during low-level flight due to friction heating of the airframe. There is a growing concern that such environmental stress in combination with the wearing of chemical/biological protective garments, G-suits, positive pressure breathing vests, and immersion suits can result in excessive thermal strain and a reduction of G-tolerance in the pilot.

Personal cooling garments may be a viable technological solution for relieving such thermal strain. Systems proposed and evaluated in recent years have included both air-cooled garments (ACGs) and liquid-cooled garments (LCGs) configured as whole-body cooling suits, cooling vests, and cooling caps (4,12,19,21–23). Operational considerations for fighter aircraft have favored liquid-cooled vests and caps, and such systems are closest to being brought into service in the near future.

The question of whether one should provide head cooling has yet to be answered. From a physiological perspective, head cooling is desirable. Nunneley *et al.* (18) demonstrated that the head is indeed a highly efficient site for heat exchange, capable of two to three times the heat removal of the torso when expressed per unit surface area, although the total heat removal capacity of the head is limited by its small area. Other reported benefits of head cooling are an increase in thermal comfort (3,18,20) and a reduction in performance impairment during heat exposure (14). One argument against head cooling is a surmised detrimental effect on the body's thermoregulatory capability due to cooling of the hypothalamus, although this has never been demonstrated under relevant circumstances.

Notwithstanding the reported successes, benefits, and advantages of head cooling in reducing thermal strain, incorporation of a liquid cooling cap into a fighter pilot helmet is not easy. Problems include increased helmet weight and difficulties with custom fitting, factors which become important during high-G maneuvres. In addition, should a fluid leak develop, there exists the potential to contaminate helmet visor de-mist air, helmet electronics, and breathing systems.

The present study was undertaken to reevaluate the need for head cooling in addition to torso cooling with an LCG with the intention of keeping helmet design simpler. Specifically, the hypothesis being tested was that head cooling is not an essential requirement for keeping thermal strain within physiologically acceptable limits. The study was carried out in a climatic chamber under environmental stress conditions that were more extreme than those generally encountered in cockpits even during severe operational circumstances (6,8,13, 15–17). Furthermore, these conditions were maintained for 3 h to ensure that the results would be applicable to the majority of operational field conditions.

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MATERIALS AND METHODS

Subjects: Six healthy males, ages 26–35 years (mean age 31), gave their written informed consent to participate in this study. Four of the subjects were civilians while two were military officers, one of these being a qualified fighter pilot. Several physical characteristics of the subjects are listed in Table I.

Chamber conditions: The study was carried out in a climatic chamber set at T_{db} = 42°C and T_{wb} = 32°C, giving a relative humidity of 50%. Radiant heat was provided to simulate a solar load by adjusting heat lamps to produce a T_g = 52°C at the head position. The resultant WBGT Index was 35°C excluding the radiant heat component to the head.

Clothing: The LCG used in this study was made by Life Support Systems Inc. (LSSI), CA, and consisted of a cooling vest and cap. Its essential structure is a set of narrow parallel channels formed by RF sealing together two layers of polyurethane-coated nylon. The fluid lines (tubes) joining the cap to the vest were cut just above the vest and fitted with single-piece male and female non-drip quick disconnects. This arrangement allowed for bypassing the flow loop of the cooling cap and permitted the same LCG to be used both with and without head cooling.

In addition to the LCG which was worn next to the skin, each subject wore a cotton long-sleeved undershirt, cotton longjohns, wool socks, a summer-weight polyester/cotton flight suit, summer flying gloves with liners, and combat boots. Head cover consisted of a Gentex DH41-2 helmet and an A13A oxygen mask with Pate suspension. The valves in the mask were removed to reduce the work of breathing, and subjects simply breathed ambient air through the valve ports.

Cooling fluid supply: Chilled fluid for the LCG was provided from an insulated reservoir containing 8 L of a 50% mixture of propylene glycol and water maintained near 10°C by a laboratory refrigeration-heating-circulation unit. The fluid temperature ranged from 10.2–10.5°C between tests but was stable to within 0.1°C during any single test. Fluid was pumped through the LCG at a rate of 0.3 L/min with an LSSI pump powered by a 6-V regulated supply.

Experimental design: Each subject was exposed once to each of 3 experimental conditions. The control condition (CTRL) involved the subject sitting in the chamber with no active cooling, but still wearing the LCG. This condition was included to ensure that the chamber environment was indeed harsh enough to require auxiliary cooling. During the vest-only cooling condition (VEST) the cooling cap of the LCG was bypassed so that fluid circulated only through the vest. Finally, during the combined torso plus head cooling condition (HEAD) fluid circulated through both the cap and the vest. The order of exposure to the 3 conditions was different for each subject to counterbalance sequence effects, and a minimum of 4 days between consecutive exposures for any one subject was used to further reduce any sequence carryover or heat acclimation effects. Subjects were not actively heat acclimated prior to the study.

TABLE I. SUMMARY OF SUBJECT CHARACTERISTICS.

Subject	Age (years)	Height (cm)	Weight (kg)
1	26	183	75.6
2	31	178	69.8
3	31	186	92.0
4	35	181	78.7
5	31	182	80.1
6	32	175	77.8

Protocol: The subject arrived at the laboratory at 0830 hours. While the rectal probe was being inserted, the undershorts were weighed to within ±1 g. At this time, the subject was encouraged to drink fluids to help offset the dehydration expected during the exposure to heat (no fluids were provided during the 3 h in the chamber). The subject was then instrumented with 12 skin thermistors and 3 ECG electrodes, weighed with leads and undershorts to within ±10 g, and dressed in the LCG, undergarments, and socks. Two 10-min expired gas collections were made with the subject seated to determine resting metabolic rate. The subject was then dressed in the remainder of the clothing and weighed fully dressed just prior to entering the chamber.

Inside the chamber, the subject was seated in an Aurora aircraft navigator's seat where he was required to perform a series of mental and motor performance tasks. Since these tasks required 20 min to complete, each exposure was divided into a series of 30-min assessment intervals which also included an expired gas collection to determine metabolic rate.

Experiments were terminated prematurely (i.e., before 3 h of elapsed time) by any one of four criteria: a) rectal temperature (T_{re}) exceeding 39°C; b) rectal temperature rise above initial T_{re} (ΔT_{re}) exceeding 2°C; c) heart rate (HR) exceeding 75% of the predicted maximum HR for each subject (220 minus age); or d) the subject requesting to leave the chamber.

Upon exiting the chamber, the subject followed the reverse of the dressing sequence, including all body weight measurements. Sweat production or fluid loss was calculated as the difference between the pre- and postexposure nude weights, while sweat evaporated was the difference between dressed weights.

Parameters measured: Body surface temperatures were measured at 12 sites using YSI 44004 thermistors. Mean skin temperature (T_{sk}) was calculated as the surface-area-weighted mean of the 12 sites (11). T_{re} was measured with a thermistor probe inserted 15 cm beyond the anal sphincter. Mean body temperature (T_b) was calculated as $0.67 \times T_{re} + 0.33 \times T_{sk}$. Body heat storage (S) was calculated as $0.83 \times$ nude body weight $\times \Delta T_b$ where ΔT_b was the difference between T_b at any time point and the initial T_b.

HR was obtained from a single lead ECG with a Tektronix 414 ECG coupled to a Quinton 611 Cardiotachometer. The output of this system was an analog voltage proportional to HR. Metabolic data obtained from the respiratory gas analyses included ventilation (V_E), oxygen consumption (V_{O_2}), carbon dioxide production (V_{CO_2}), and respiratory exchange ratio (RER).

Motor performance and coordination were assessed by scoring the number of ball bearings the subject could place into a narrow vertical tube in 40 s using a pair of forceps. Mental performance was assessed by scoring errors made and time required to complete a page of mental arithmetic, and by scoring errors made and number of lines of random letters scanned in 15 min looking for the letter "E." These three tasks were presented to the subject in random order during each 30-min assessment interval throughout the entire exposure. All subjects were trained to plateau performance levels prior to the study.

Subjective evaluations of thermal comfort for the head, chest, and whole body were obtained by having the subject mark three 10-cm lines labelled "Completely Comfortable" and "Absolutely Intolerable" at their ends. These evaluations were performed prior to entering the chamber and at 30-min intervals thereafter. For each evaluation, the labels at the ends of the lines were reversed to help reduce any memory effects of the previous subjective assessment. After completion of the entire set of exposures, each subject was asked to complete a questionnaire.

Data acquisition/analyses: All thermistors and the cardiotachometer output were scanned continuously by a Hewlett-Packard computer-controlled data acquisition system. At 2-min intervals (approximately 12 scans) the mean values for all parameters over the 2-min interval were calculated and stored on disk for subsequent processing and analyses. Any parameters not stored on disk in real time (e.g., metabolic data, comfort data, body weights, performance scores, etc.) were later entered into the computer via the keyboard.

The experimental hypothesis was tested using Student's paired *t*-test to compare the VEST and HEAD conditions. For most parameters recorded, it was either final values or changes (Δ's) over the exposure duration that were of interest. Parameter differences were considered significant at $p \leqq 0.05$. Condition CTRL was not essential to this hypothesis and could have been omitted from the study. Its inclusion, however, added confidence to the results concerning the value of auxiliary cooling. The data for condition CTRL are therefore presented for reference only and were not included in the statistical analyses.

RESULTS

Physiological response summary: Table II contains a summary of the physiological responses obtained under all three test conditions. Values presented are the mean ± S.E.M. over six subjects. Also presented are the probability values from Student's paired *t*-test comparing conditions VEST and HEAD for each parameter.

Tolerance times: The tolerance times for exposure to condition CTRL ranged from 60–102 min, with an average tolerance time of 83 min. Reasons for termination of the exposures included high HR (1 case), high T_{re} (1 case), high ΔT_{re} (1 case), and requests for withdrawal by the subjects themselves (3 cases). Several subjects complained of headache or dizziness, some had difficulty breathing or were hyperventilating, and one subject vomited 20 min after exiting the chamber.

In contrast, all but one subject on one occasion (condition VEST) completed 3 h in the chamber under both cooling conditions. Since that particular exposure was abbreviated by 8 min, all data for all subjects were truncated at 172 min for all subsequent comparisons. However, for simplicity, conditions VEST and HEAD will be referred to as nominally having lasted a full 3 h.

From these results, it is clear that the chamber conditions were indeed severe and intolerable without auxiliary cooling. Furthermore, it can be seen that the LCG operating in either condition (i.e., with or without head cooling) provided adequate protection to extend the tolerance times to at least 3 h.

Rectal temperature responses: There was considerable variation in final T_{re} between subjects at termination of exposure CTRL. However, since exposure times

TABLE II. SUMMARY OF PHYSIOLOGICAL PARAMETERS.

Parameter	CTRL	VEST	HEAD	p
Tolerance Time (min)	83 ± 7	179 ± 1	180 ± 0	0.36
T_{re} (°C)	38.3 ± 0.2	37.8 ± 0.2	37.6 ± 0.1	0.12
ΔT_{re} (°C)	1.3 ± 0.2	1.0 ± 0.2	0.7 ± 0.1	0.05
T_{sk} (°C)	38.3 ± 0.2	35.5 ± 0.2	35.4 ± 0.1	0.59
ΔT_{sk} (°C)	4.0 ± 0.2	1.1 ± 0.3	1.0 ± 0.2	0.75
T_b (°C)	38.3 ± 0.1	37.0 ± 0.2	36.9 ± 0.1	0.24
ΔT_b (°C)	2.2 ± 0.2	1.0 ± 0.2	0.8 ± 0.2	0.13
S (kcal)	144.8 ± 12.4	67.9 ± 14.3	52.4 ± 9.6	0.13
HR (bpm)	131 ± 3	110 ± 19	94 ± 2	0.07
F_{LOSS} (kg)	1.096 ± 0.205	0.816 ± 0.143	0.671 ± 0.090	0.21
DEHY (%)	1.4 ± 0.3	1.0 ± 0.2	0.8 ± 0.1	0.17
F_{EVAP} (kg)	0.213 ± 0.053	0.223 ± 0.047	0.143 ± 0.027	0.14
V_E (L/min)	13.043 ± 1.992	11.231 ± 2.778	8.245 ± 0.569	0.28
V_{O_2} (L/min)	0.397 ± 0.037	0.380 ± 0.058	0.341 ± 0.015	0.48
V_{O_2} ($ml \cdot kg^{-1} \cdot min^{-1}$)	4.980 ± 0.307	4.793 ± 0.662	4.331 ± 0.107	0.49
V_{CO_2} (L/min)	0.403 ± 0.046	0.326 ± 0.053	0.277 ± 0.015	0.32
RER	1.007 ± 0.043	0.855 ± 0.026	0.810 ± 0.022	0.19

Values are mean ± S.E.M. for 6 subjects.
Data are based upon values at 172 min for conditions VEST and HEAD, or final values obtained during condition CTRL.
Statistical results are based on Student's paired *t*-test between conditions VEST and HEAD.

varied so much between subjects for a variety of reasons as explained above (most of them not related to T_{re}), the value of discussing final T_{re} with respect to thermal strain under this test condition is questionable.

During conditions VEST and HEAD, all subjects tolerated a nominal 3 h of exposure, and the T_{re} values at 172 min can be meaningfully compared. Final T_{re} ranged from 36.9–38.4°C during condition VEST, with a mean value of 37.8°C, while during condition HEAD final T_{re} ranged from 37.2–37.8°C with a mean value of 37.6°C. As shown in Table II, the values for final T_{re} did not differ significantly between conditions VEST and HEAD.

Fig. 1 provides a summary of T_{re} plotted against time for all three test conditions. Note that the curve for condition CTRL has "discontinuities" whenever the number of subjects in the mean decreases due to variations in tolerance times.

Since all subjects started the exposures at slightly different values of T_{re}, individual responses were "normalized" by looking at ΔT_{re} after 3 h (172 min) of time in the chamber. During condition VEST, ΔT_{re} ranged from 0.5–1.6°C with a mean value of 1.0°C, while during condition HEAD, ΔT_{re} ranged from 0.3–1.2°C with a mean value of 0.7°C. Statistically, ΔT_{re} was significantly different (marginally) between conditions VEST and HEAD. Because the mean values of initial T_{re} for the three test conditions were so similar, plots of mean ΔT_{re} against time are not shown but can be inferred by subtraction of approximately 37°C from the ordinate of Fig. 1.

Mean skin temperatures: Fig. 2 is a summary of the T_{sk} responses in the three test conditions. It is clear again that condition CTRL differs greatly from conditions VEST and HEAD. Final mean values for T_{sk} are listed in Table II. All these values are well above the normal comfort level of 33°C for T_{sk}, and heavy sweating occurred under all three test conditions (see below). Statistically, final T_{sk} did not differ significantly between conditions VEST and HEAD.

As shown in Fig. 2, during conditions VEST and HEAD, T_{sk} values were lower than during condition CTRL. However, plots of individual skin temperatures indicated that this lowering of T_{sk} under both cooling conditions was due predominantly to lower skin temperatures on the torso at those sites covered by the cooling vest. Fig. 3, showing data for one subject during condition HEAD, is representative of the skin temperature responses in all subjects under both cooling conditions and shows that apart from those sites directly under the LCG (i.e., sites 2, 4, 10, and 11), skin temperatures were generally between 36–38°C after 30 min in the chamber. The only exception to this was the foot temperature which rose rather slowly, probably because of the insulation provided by the socks and boots.

In fact, when the skin temperature data from the cooling conditions were compared visually with the data for condition CTRL it was observed that all skin sites not

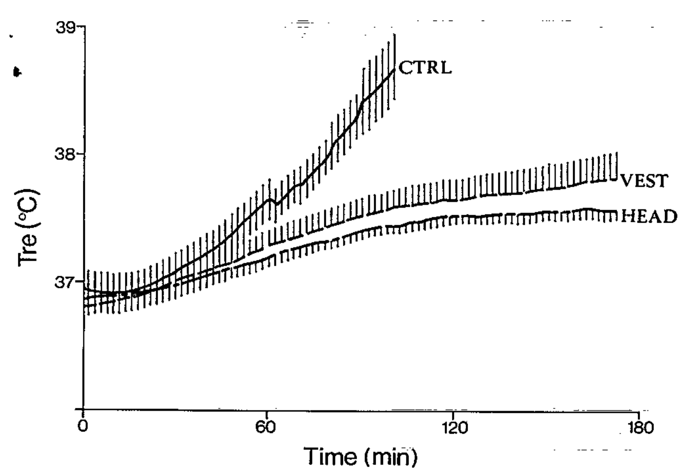

Fig. 1. Mean T_{re} averaged over 6 subjects vs. time for conditions CTRL, VEST, and HEAD. Vertical bars represent the S.E.M. at each 2-min data point. Error bars for conditions VEST and HEAD overlap; therefore only half-bars have been drawn for clarity.

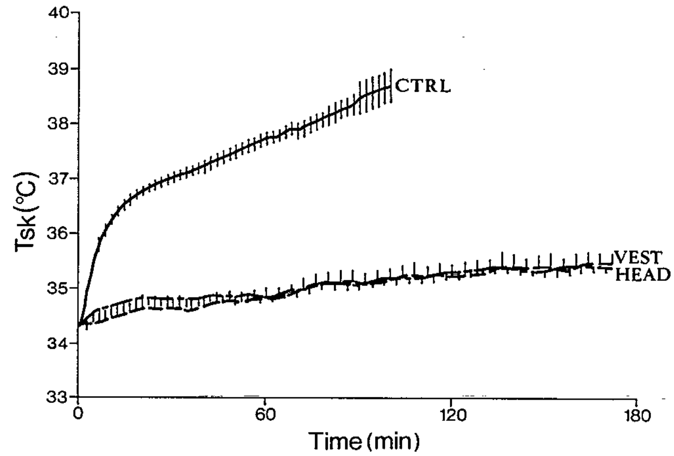

Fig. 2. Mean T_{sk} averaged over 6 subjects vs. time for conditions CTRL, VEST, and HEAD. Vertical bars represent the S.E.M. at each 2-min data point. Error bars for conditions VEST and HEAD overlap; therefore only half-bars have been drawn alternately at 4-min points for clarity.

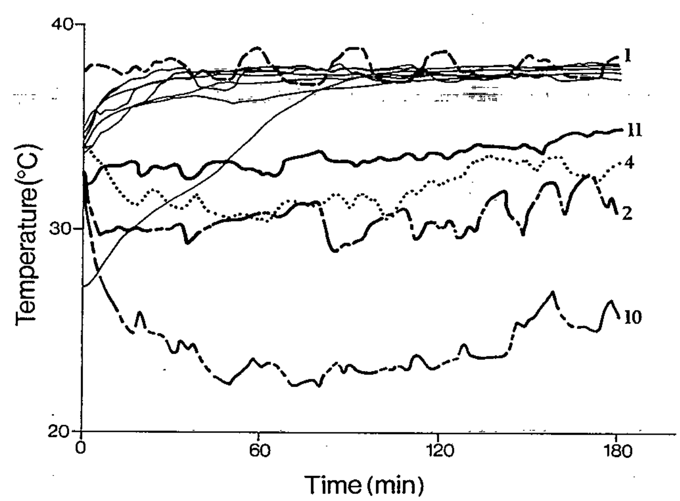

Fig. 3. Individual skin temperatures vs. time from 1 subject during condition HEAD. Sites 2, 4, 10, and 11 are chest, abdomen, upper back, and lower back, respectively; foot temperature is the curve rising slowly from 27°C over 90 min; forehead temperature (site 1) is the curve exhibiting cyclic variations; the remaining sites are not identified.

covered by the LCG rose to similar levels at similar rates during the early portion of the exposure under all three test conditions. The surface cooling effect of the LCG was, therefore, very localized.

Note that the skin temperatures under the LCG ranged from the low 20's to the low 30's. Overall there was considerable variability in these temperatures, probably the result of variations in the degree of contact between the LCG and the body at the thermistor measuring site.

Fig. 3 was intentionally selected from condition HEAD to show that even forehead temperature was not markedly reduced by head cooling with the LSSI cooling cap, re-affirming that the LCG cooling effect is quite localized. (The forehead temperature, site 1, is the one cycling in Fig. 3, possibly indicating waves of vasodilation and vasoconstriction; the forehead thermistor was not covered by the cooling cap.)

Mean body temperature/heat storage: Final values of T_b and ΔT_b are listed in Table II. Statistically, there was no significant difference between final T_b or between ΔT_b during conditions VEST and HEAD.

The ΔT_b values can be converted to joules of heat storage by multiplication with body weight and the factor $3.4736\ J \cdot g^{-1} \cdot {}^{\circ}C^{-1}$. While this procedure yields acceptable SI units, most researchers are probably more familiar with total kilocalories of body heat storage. Accordingly, S was calculated as described earlier in Methods, and the data presented in Table II are in kcal. Statistical conclusions for S were the same as for the ΔT_b data: no significant difference between conditions VEST and HEAD.

Heart rate: Fig. 4 shows HR data obtained in this study. Since HR generally fluctuates more rapidly than temperature, the 2-min HR data stored on disk were processed by averaging over 10-min intervals. It is these 10-min average HR values that were then averaged over the 6 subjects to obtain the data points presented in Fig. 4. The data are plotted at the midpoint of the 10-min averaging interval, with final mean values presented in Table II.

Once again, condition CTRL stands out against the

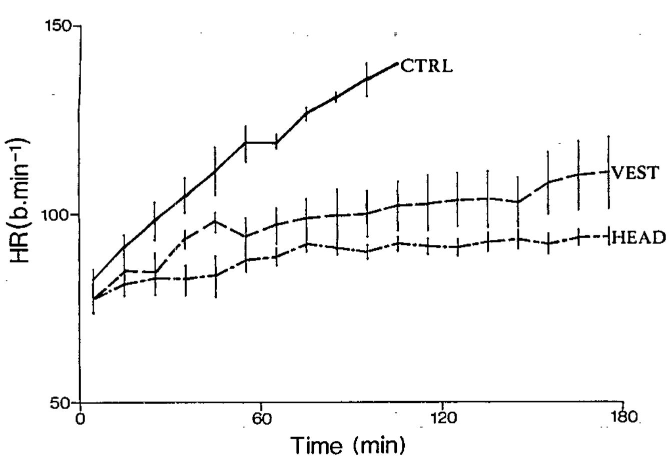

Fig. 4. Mean HR averaged over 6 subjects vs. time for conditions CTRL, VEST, and HEAD. Data points are averages over 10-min intervals plotted at the midpoint of each interval. Vertical bars represent the S.E.M. at each point.

two cooling conditions, confirming the need for and value of auxiliary cooling. Although it would appear that the final mean HR values of 110 bpm and 94 bpm for conditions VEST and HEAD, respectively, are quite different, the difference was not statistically significant.

Body weight measurements: Arithmetic manipulations of the six weights recorded for each subject during each exposure yielded several parameters. Total fluid loss (F_{LOSS}) was calculated as the net change in nude weight, and was converted to percent dehydration (DEHY) by division with the preexposure nude weight. One subject reached 2.4% dehydration during condition CTRL and stayed home the next day due to malaise.

Fluid evaporated (F_{EVAP}) was calculated as the net change in dressed weight. This weight parameter was more susceptible to error since the amount of fluid left in the LCG upon exiting the chamber was difficult to control. Also, it is possible that atmospheric moisture may have condensed on the LCG, thereby offsetting weight losses from evaporation of body sweat. Nevertheless, taking the heat of vapourization to be 0.58 kcal/g, we see that evaporation of sweat may have removed an average of 124, 129, and 83 kcal of heat from the body during conditions CTRL, VEST, and HEAD, respectively.

Statistical analyses performed on all three weight parameters showed no significant differences between conditions VEST and HEAD.

Metabolic results: Analyses of the expired respiratory gas samples yielded measures of ventilatory rate, oxygen consumption, carbon dioxide production, and respiratory exchange ratio, and the results are shown in Table II. All parameters exhibited the already familiar pattern of decreasing stress from condition CTRL, through VEST, to HEAD. However, comparison of conditions VEST and HEAD showed no statistically significant differences in the final values of any of the parameters.

Performance tests: The three performance tests yielded five scoring parameters that were averaged over the six subjects and plotted against time. These data are not presented since the three exposure conditions were almost indistinguishable from one another. There were, however, some interesting trends in the data.

Manual dexterity (number of ball bearings placed into the tube) was virtually identical under all three test conditions, showing a marginal improvement in scores as time within the exposure progressed.

The math test yielded two scorable parameters—number of errors, and completion time. For errors, there was no difference between conditions, and performance was stable as a function of time. Completion time was also not different between conditions, but dropped slightly with time in the environment.

The letter scan test was analyzed for the number of errors made and the number of lines completed in each 15 min period. Conditions VEST and HEAD showed no differences in either parameter between conditions, and the number of lines completed under both conditions increased slightly before leveling off as a function of time in the environment. Condition CTRL was somewhat unique in this test, indicating a slight increase in number of lines scanned and in number of errors made near the end of the exposure.

Subjective thermal comfort: Analyses of the comfort scores showed highly significant differences between conditions VEST and HEAD for the body as a whole and for the head, but no significant differences for chest comfort. This is not surprising, considering that the chest received cooling under both test conditions. Also as expected, condition CTRL was the most uncomfortable test condition in terms of comfort at all three body locations.

Examination of the time course of the comfort scores showed that both the head and the whole body were at 40–60% of the maximum discomfort level within the first 30 min of exposure during conditions VEST and HEAD; by comparison, chest discomfort required almost 60 min to reach similar levels. However, all comfort scores were at their maximum discomfort values by 90 min of exposure to these conditions.

Finally, all subjects filled out a questionnaire after completion of the study. All subjects unanimously agreed that body cooling was essential for the conditions in the chamber. All but one subject felt that head cooling in addition to torso cooling was desirable but not necessary (this one subject felt it was both desirable and necessary), and no one felt it was undesirable. When asked if their performance was affected by the heat, the results were inconclusive. Most of the subjects felt, however, that there were no differences in their performances between conditions VEST and HEAD, a result borne out by the performance scores themselves.

DISCUSSION

The null hypothesis being tested in this study was that head cooling in addition to torso cooling is not necessary to maintain thermal strain in fighter pilots within physiologically acceptable limits. Accordingly, subjects were exposed to high (but operationally possible) ambient temperatures for extended periods, and thermal strain was assessed by monitoring several physiological parameters directly and by deriving other parameters from these direct measures. Of all parameters examined, both direct and indirect, only ΔT_{re} showed a marginally statistically significant difference between conditions VEST and HEAD, with values of 1.0°C and 0.7°C, respectively.

The statistical significance of this arithmetically derived result not withstanding, it is important to interpret this finding in the light of its physiological significance. Specifically, one must question whether a difference of 0.3°C in ΔT_{re} is important, given the absolute values of T_{re} and ΔT_{re} encountered in this study. Elevations in T_{re} of these magnitudes are quite common in response to physical work alone, even in the absence of environmental thermal stress (2). In fact, the values of final T_{re} recorded during the two cooling conditions are not much above levels that would be considered normal simply as a result of diurnal variations. Taking this and all other physiological parameters into account, the importance of this single statistically significant result was deemed to be minimal from a thermal strain viewpoint.

Additional support for this conclusion is found in the performance test results. For the most part, this study showed no performance decrements in the subjects under any of the conditions tested, a result that is consistent with the hypothesis that mild heat strain can improve performance slightly. Similar results have been reported by others (7,9,10,23), although such findings are inconsistent with the results of Allan *et al.* (1) and Gibson and Allan (5) who showed that on a rotary pursuit task performance impairments begin at a T_{re} as low as 37.6°C. It is quite likely that different faculties of the human brain have different thresholds for impairment decrement, and it may be that the tests employed in this study were not as sensitive to body temperature rises as the tests of Allan *et al.* Nevertheless, the performance test results obtained in this study are not unexpected, and they support the conclusion that condition VEST was not significantly different from condition HEAD.

In deference to those studies that did show head cooling is important, one should not overlook the subjective evaluations of comfort by the subjects themselves, even though the relationship between thermal comfort, thermal strain, and performance is not definitively known. The questionnaire responses indicated that if head cooling were available, most subjects would elect to use it. Furthermore, no one disliked head cooling, and no one claimed it was too cold on the head. These subjective comments suggest that head cooling is desirable if it can be made available in a practical manner. However, returning to the original purpose of this study, the provision of head cooling in a fighter pilot helmet using a liquid cooled cap was considered to be technologically difficult, and this study was investigating the necessity, not the desirability, of head cooling.

Taking all data from this study into account, and considering that the test conditions were longer and hotter than generally expected in fighter aircraft operations, it was concluded that head cooling in addition to torso cooling is not necessary for maintaining thermal strain within physiologically acceptable limits.

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