The effect of head cooling on cardiovascular and thermal responses to exercise in the heat.

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Abstract

This study evaluated the effects of a liquid conditioned hood on the cardiovascular and thermal responses to a brief work/rest protocol in a hot environment. The chamber was set at dry bulb temperature 40°C, wet bulb temperature 30°C and relative humidity 40 %. The hood was made of stretch nylon with approximately 17 m of PVC tubing (inside diameter 2 mm, outside diameter 2.5 mm) sewn onto the inner surface (The hood was kindly loaned by the Centre for Human Sciences – Qinetiq). Water flow through the hood was set at 0.8 L/min via a 24V liquid pump and the water temperature was maintained at 8-11°C using a refrigerated cooler unit and a heating unit with a thermostat. The volunteer subjects who were six healthy men participated in two 80 minute work/rest trials. The protocol was divided into 10 min exercise on a cycle ergometer with an external load of 150 W followed by 10 min rest – repeated 3 times with a final recovery period of 30 min. In one trial subjects had their head cooled during each rest period (COOL) and in a second trial no cooling was provided (CONT). Cooling effects were evaluated by recording tympanic temperature, mean skin temperature, scalp temperature, heart rate, forearm blood flow, sweat rate and a subjective comfort assessment.

Head cooling during rest periods caused a reduction in tympanic temperature, scalp temperature and heart rate which continued into subsequent exercise periods. The recovery of heart rate during each rest period was more rapid in COOL. Mean skin temperature was not affected by cooling at all. Subjective ratings of *head*, *body* and *overall* thermal comfort at the beginning and end of each rest period were improved by head cooling. Forearm blood flow was measured at the beginning and end of each rest period and was also significantly reduced by head cooling. Overall sweat rate was reduced by 30% in the COOL condition. These results suggest that, when used during rest periods between brief work/rest cycles in the heat, head cooling both enhances recovery and attenuates the cardiovascular and thermal responses to subsequent exercise. Benefits of head cooling during brief work/rest cycles in a hot environment include a reduced sweat rate, lower heart rate and improved thermal comfort.

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Introduction

A common strategy for reducing the effects of heat stress in both a military and industrial setting is to introduce rest periods between bouts of physical work in the heat. Another strategy for improving the capacity of man to function in a hot environment is to provide some form of personal conditioning system. Previous investigations have highlighted the effectiveness of liquid conditioned garments in enhancing heat loss and reducing physiological symptoms of heat strain (Shvartz, 1970; Nunnely *et al.*, 1971; Blair and Harrison, 1977). On the basis of these observations it is the purpose of the present study to investigate the effectiveness of head cooling, during rest periods only, in reducing the cardiovascular and thermal strain associated with exercise in the heat.

Personal Conditioning Systems

Liquid conditioned garments were developed in the UK as a means of alleviating thermal strain associated with hot environments, initially for military aircrew. Cockpit temperatures have been shown to reach peaks of 50°C during ground standby and taxi in a study of desert operations in the F111-A aircraft (Nunneley and James, 1977) and the F4 aircraft (Nunneley et al., 1981). Although the energy expenditure associated with piloting these aircraft has been shown to be equal only to that of walking (Thornton *et al*., 1984), the thermal stress imposed by these environmental conditions is a major contributor to physiological and performance decrements in the heat. Thus there is a clear need for personal conditioning systems within the military. Liquid conditioned garments were adopted by NASA, for use in the space programme, as a means of providing the astronaught with personal conditioning within the full coverage pressure suit. The liquid cooled garment commonly consists of PVC pipe-work sewn onto the inner surface of a stretch nylon garment, through which cool water is pumped (Blair and Harrison, 1977). The circulation of cooled water is intended to remove metabolic and environmental heat from the skin surface via conduction (Shvartz *et al*., 1974). Numerous investigations have identified the potential for water-cooled garments to alleviate physiological indices of heat strain. Studies have also demonstrated a link between convective cooling, improved sensation of thermal comfort and attenuation of psychomotor performance decrements caused by heat stress (Nunneley *et al*., 1982).

A common conditioning hood design comprises approximately 17 m of tubing through which cooled water is pumped (Blair and Harrison, 1977). Using a flow rate of 10 $g \bullet s^{-1}$ with a mean inlet temperature of 6°C, these investigators demonstrated a maximum heat removal of 100 W with subjects seated at rest in environmental conditions 50°C (dry bulb) and 37°C (wet bulb).

An investigation by Nunneley *et al.* (1971) compared head cooling with a bare-headed control over a range of environmental temperatures (20°C to 40°C). In this study, the cooling cap was shown to remove an average of 30% of resting metabolic heat (Nunneley *et al*., 1971). More recently, the potential for effective head cooling has been reinvestigated (Cohen et al., 1989). The development of the European Fighter Aircraft (*Eurofighter*) has lead to a renewed focus upon alleviation of thermal strain in aircrew. The modern fighter pilot must wear extra layers of vapour impermeable clothing required for Nuclear Biological and Chemical (NBC) protection coupled with the added thermal load of anti-G garments. Initially, a liquid conditioned vest was developed and was shown to effectively reduce the rise of core temperature in heat stress (Hayes *et al*., 1986, Cohen *et al*., 1989). With the addition of head cooling (inlet 13°C) to the cooling vest (inlet 15°C) however, subjects reported improved head comfort during a 2 hr exposure to a 40°C environment while wearing Aircrew Chemical Defence clothing (Cohen et al., 1989).

The present study therefore aims to investigate the effects of head cooling upon cardiovascular responses to heat exposure, primarily heart rate and limb blood flow. It is also of interest to determine the effects of head cooling made available to the subject during periods of rest only, following a period of physical exercise. This may have applications for the ground crew in a military setting, who would only be able to use the garments during rest periods between working on aircraft. Thus, the design of the current study incorporates this notion and employs an alternating work-rest cycle protocol with cooling of the head only in the rest periods.

Methods

Subjects

Six subjects (all male) volunteered to participate in the study. They gave their informed consent after completing a medical examination to ensure there were no underlying health problems. All subjects were given information regarding the purpose, procedures, potential risks and hazards and withdrawal criteria for the study. Ethical approval was obtained from the King's College London ethics committee. The mean ± standard deviation (SD) age, height and weight were: 21 ± 2 yrs, 172 ± 5 cm and 71.8 ± 5.5 kg respectively. Subjects were all unacclimatised to heat and had not recently spent time in a hot environment.

Liquid Conditioned Hood and Clothing

The liquid conditioned hood was designed and manufactured by the Engineering Physics Department of the Royal Aircraft Establishment, Farnborough, UK (Brown and Williams, 1982). The hood was made of stretch nylon with approximately 17 m of PVC tubing (inside diameter 2 mm, outside diameter 2.5 mm) sewn onto the inner surface of the hood (Figure 1.0). Each subject wore the liquid conditioned hood in both experimental conditions. The hood was covered with an RAF type-G helmet lined with a layer of cotton wool.

Figure 1.0 The Liquid Conditioned Hood.

Coolant supply to the liquid conditioned hood

A water bath (Grant Instruments Ltd, Cambridge) was located in a room next to the climatic chamber. The water was kept cold using a refrigerated cooler unit (Grant Instruments Ltd, Cambridge) and maintained at around 8°C using a heating unit with a thermostat. Water was circulated through the hood by a 24V liquid pump (VDO, Germany), powered by a Weir 413D Power Supply (Weir, Bognor Regis). The flow was maintained at 0.8 L/min for all subjects.

Procedures

Subjects performed two trials in either a head cooling (COOL) or a control – no cooling – (CONT) condition, the order of which was randomised. During both conditions the hood was worn but it was connected to the supply of cool water during rest periods in the COOL trial only. The chamber was maintained at an ambient temperature of 40°C (dry bulb) and 40% relative humidity.

The timed exposure began when the subject began to cycle on a Monark cycle ergometer (Ergomedic 818E – Monark, Sweden). Each subject cycled for 10 minutes, initially at 150 W at a pedal rate of 60 rpm however this was reduced to 120 W for those subjects whose heart rate rose above 165 beats.min^{-1}. In this case, the same work protocol was adopted for the second condition. Following the initial work period the subject was seated at rest for a further period of 10 minutes. This protocol was repeated for a total of 3 exercise periods, each followed by 10 minutes rest except for the final exercise period, which was followed by 30 minutes seated recovery. Total exposure time was approximately 85 minutes (5min instrumentation; 10min exercise; 10min rest; 10min exercise; 10min rest; 10min exercise; 30min rest).

Measurements

Mean skin temperature was calculated from a weighted mean of arm, chest, thigh and shin temperature measurements using the equation described by Ramathan (1964). Scalp temperature was also measured with a thermister placed on the Superior aspect of the scalp (between cooling tubes).

ECG was monitored continuously and heart rate was recorded from the display at the beginning of each period and at 2 minute intervals, as for the temperature readings.

Blood flow was measured in the right forearm by venous occlusion plethysmography with subjects seated at rest. A rubber strain gauge containing mercury was attached around the right forearm at the level of greatest circumference (Whitney, 1953). Recordings of forearm blood flow were made over 3 to 4 minute periods at the beginning and at the end of each rest period and at 5 minute intervals over the final 30 minute rest period.

A subjective rating of thermal comfort was obtained using a 10 cm line (Gedye *et al.*, 1961) marked at either end with ‘perfectly comfortable’ (zero) and ‘absolutely intolerable’ (10 cm) (Nunneley *et al.*, 1982).

The inlet (T_{in}) and outlet (T_{out}) temperatures of the water flowing to and from the hood were measured by thermistors inserted into the connecting pipes at approximately 30 cm from the hood. Both T_{in} and T_{out} were recorded every 2 minutes during rest periods in the COOL trial only, via a digital thermometer. These measurements were then used to calculate heat exchange (ΔH) across the hood.

Results

All six subjects were able to complete the entire work-rest protocol. The environmental conditions chosen for the present study (40°C dry bulb, 30°C wet bulb and 40 % relative humidity) were representative of the high temperatures encountered by individuals on the ground during hot summers in a tropical climate.

Head cooling (COOL) produced a more rapid reduction in heart rate during rest periods, which then remained lower than the CONT group during each rest period (Figure 2.0). Although the lower heart rate in the COOL condition was evident during all three rest periods, the differences were more pronounced during the 2nd and 3rd rest periods. Here the significant difference between COOL and CONT was around 15 beats min^{-1} ($p<0.01$). During the final 30 minute rest period (rest 3) final heart rate in the COOL condition returned to within 10 beats min^{-1} of baseline, whereas in the CONT condition heart rate remained elevated and the final heart rate was still 18 beats min^{-1} above the resting baseline. This difference in final heart rates between COOL and CONT was also significant ($p<0.05$).

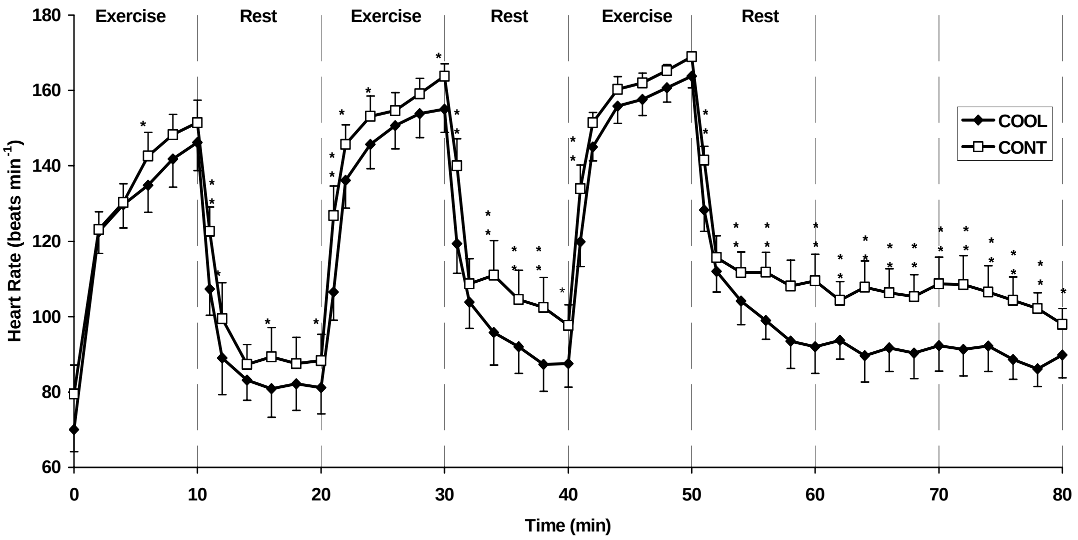

Figure 2.0Mean ± SE heart rate (beats per minute) during work rest cycles in either head cooling (COOL) or control (CONT) conditions.
* COOL significantly lower than CONT ($p < 0.05$) ** ($p < 0.01$)

While scalp temperature continued to rise in both COOL and CONT conditions during exercise periods, cooling maintained the scalp temperature significantly below CONT levels even during exercise ($p<0.01$). During the final 2 minutes of each exercise period however, the difference in scalp temperature between COOL and CONT was not significant.

Skin temperature was measured at the shin, thigh, arm and chest and mean skin temperature calculated using the equation:

Mean Skin = $0.3\, t_{chest} + 0.3\, t_{arm} + 0.2\, t_{thigh} + 0.2\, t_{leg}$ Ramathan (1964)

Although skin temperatures in both COOL and CONT rose and fell in line with the other variables, which followed the exercise-rest protocol there was no significant difference between the mean skin temperature in the two conditions. Thus, mean skin temperature was not significantly affected by head cooling. Maximum mean skin temperature was 36.9°C in both conditions at the end of the third exercise period.

The mean values for forearm blood flow were significantly different ($p<0.05$) during the first rest period where COOL blood flow was 6.1 ± 0.6 and 6.5 ± 0.9 ml/100ml/min for recording 1 and 2 respectively compared to 11.5 ± 2.8 and 10.1 ± 3.2 ml/100ml/min for the same points in the CONT condition. Although forearm blood flow continued to be lower in the COOL condition during the second rest period, this was not significant. The greatest difference between the two conditions occurred during the final rest period at the 7 – 9 min point when COOL blood flow was 9.5 ± 1.6 ml/100ml/min compared to 15.7 ± 3.2 ml/100ml/min for the CONT condition.

Subjective ratings of thermal comfort were consistently lower in the COOL condition at each time point following the first exercise period. Both body and overall comfort along with head were significantly ($p<0.01$) improved at the 20 minute point, the end of the first cooling period. Although all regions were subjectively less comfortable after the second exercise period (30 min) again COOL was significantly ($p<0.01$) more comfortable than CONT.

The temperature of both the water flowing to (T_{in}) and from (T_{out}) the hood was recorded every 2 minutes during rest periods in the COOL trial only. These measurements were then used to calculate heat exchange (ΔH) across the hood from the equation;

$$\mathbf{\Delta H = m \bullet c \bullet (T_{in} - T_{out})} \qquad \text{(Eq.1)} \qquad \text{Harrison and Belyavin (1978)}$$

Where **ΔH** is the heat lost or gained in Watts

m is the mass flow of the cooling liquid in $g \bullet s^{-1}$

c is the specific heat of the cooling liquid in $J \bullet g^{-1} \bullet °C^{-1}$

$T_{in} - T_{out}$ is the change in temperature – the gradient across the hood

In the present study water was used as the cooling liquid and so **c** is a constant 4.2 $J \bullet g^{-1} \bullet °C^{-1}$. As the mass flow was also kept constant at 800 g/min, the value of **m** was also a constant at 13.3 $g \bullet s^{-1}$ thus making the product of **$m \bullet c$** a constant, **K**, where;

$$\mathbf{K = 13.3 \times 4.2 = 55.86\ J \bullet °C \bullet s^{-1}}$$

Thus Eq.1 becomes;

$$\mathbf{\Delta H = 55.86 \bullet (T_{in} - T_{out})} \qquad \text{(Eq.2)}$$

The data from heat exchange across the hood (Watts) are given in Figure 2.1. During each rest period the inlet temperature slowly increased due to the return of warmed water to the water bath. When the inlet temperature exceeded 11 °C ice was added to the bath in order to maintain a low inlet temperature.

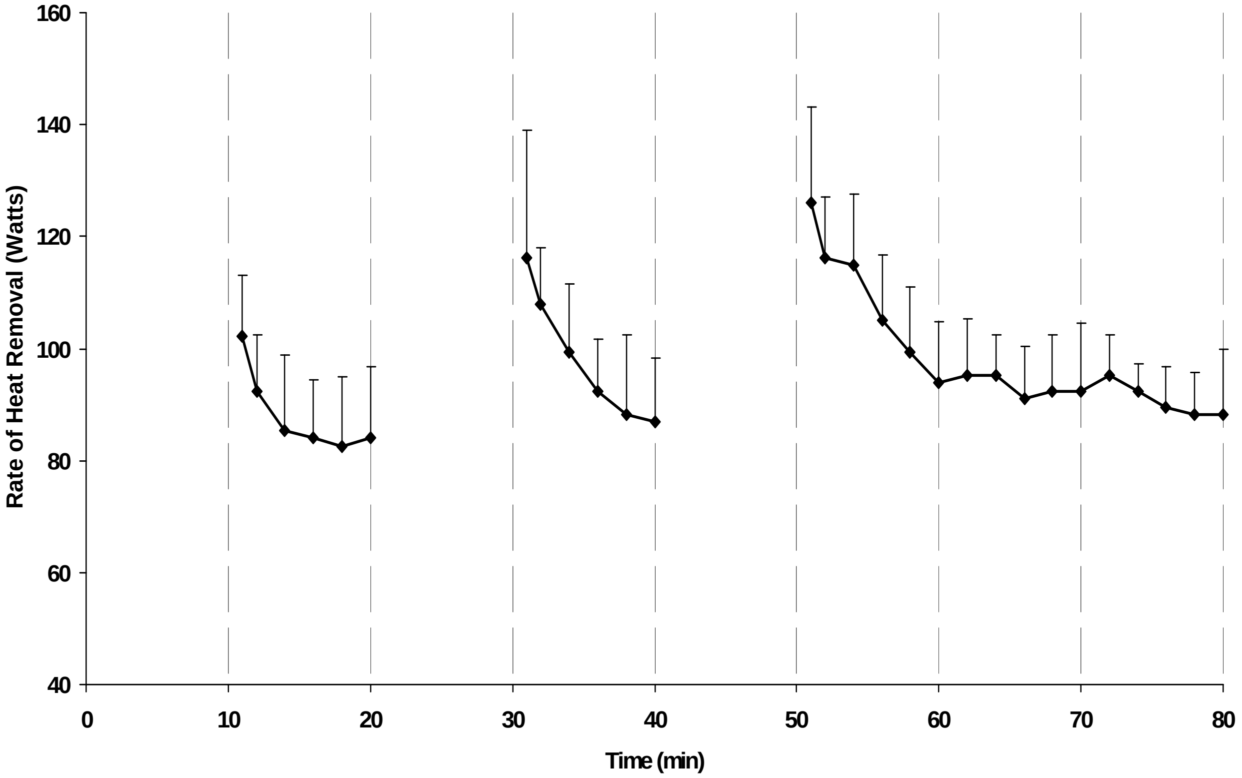

Figure 2.1 Mean ± S.E. rate of heat removal (Watts) through the liquid conditioned hood during each rest period of the work-rest protocol

Maximum rates of heat exchange occurred during the first minute of cooling with mean ± S.E. peaks of 102 ± 10.9, 116.2 ± 22.9 and 126.0 ± 17.1 Watts during rest periods 1, 2 and 3 respectively. Heat exchange then declined so a similar level during each of the three rest periods. Final mean ± S.E. values for each of the rest periods 1, 2 and 3 were 84.0 ± 12.9, 86.8 ± 11.6 and 88.2 ± 11.6 Watts respectively.

Discussion

Results of the current investigation demonstrate a reduction in the cardiovascular and thermal responses to exercise in a hot environment as a result of head cooling. When used during rest periods only, head cooling was shown to attenuate the thermal and cardiovascular responses to a subsequent period of exercise. Head cooling also served to enhance the recovery from brief periods of exercise in the heat.

Brief work-rest cycles are commonly used by industry and the military as a practical method of reducing the effects of intolerably hot environments. It is becoming increasingly important to provide improved efficiency of work/rest cycles due to the added insulation of protective clothing. One important determinant of comfort and task performance in the heat is the subjective assessment of head thermal comfort. A personal liquid conditioning system for head cooling has been evaluated in terms of it’s effects upon the cardiovascular and thermal effects of work/rest cycles in the heat.

Our subjects commented that the inlet temperature was satisfactory and that they would not have required it to be any cooler. Previous experiments have shown that cooling hoods can provide around 100 W of cooling with a mass flow of 10 $g.s^{-1}$ (Blair and Harrison, 1977). The results of the present study show maximum cooling capacity to be higher than this at 126 W during the final rest period. The reason for the higher heat removal in the present investigation is probably due to the higher flow rate, 13.3 $g.s^{-1}$, which would provide a greater value for **k** in the heat exchange equation of Harrison and Belyavin (1978). Higher rates of cooling of up to 140 W have been reported for a different hood design with flow rates of 12.5 $g.s^{-1}$ (Nunneley *et al*., 1971). In the study of Nunneley *et al*. (1971) subjects were allowed to select the inlet temperatures, which may explain the difference in cooling capacity. It must be recognised that only part of the heat removed by the hood is metabolic heat. While attempts were made to insulate the hood using an RAF type-G helmet, and the inlet pipe work using cotton wool, the neck area of the hood remained exposed to the environment.

The results of the current investigation provide support for the suggestion by Nunneley et al. (1982) that head cooling may affect human thermoregulation by a combination of three possible mechanisms:

1. a change in overall body heat balance
2. counter-current effect on temperature of blood supply to the brain
3. alterations in sensory input from the skin (scalp) thermoreceptors.

Whatever the combination of these mechanisms it is probable that artificial cooling of the head reduces the internal and external thermal stimuli to the hypothalamus, thus reducing stress on the thermoregulatory system. The net result of these effects are the reduced demand for sweating, skin blood flow, and possibly cardiac output - a notion supported by the data from the current investigation.

Results of the current investigation also support the notion that head cooling has a more prominent effect upon internal body functions than external ones (Williams and Shitzer, 1974). While the rise in aural temperature, sweat rate, heart rate and forearm blood flow was attenuated with head cooling, mean skin temperature remained fundamentally unchanged from control over much of the experiment. The mean skin temperature showed no effect of head cooling during each rest period. Although previous authors have found similar results (Williams and Shitzer, 1974), the data for the final rest period show a trend towards a reduction in mean skin temperature with more prolonged cooling. Williams and Shitzer (1974) have suggested that mean skin temperature will not be affected by head cooling as it remains dominated by the environmental temperature. If this were the case, then the mechanisms affecting variables such as sweat and heart rates in the current study may be more central in origin. In contrast however Kissen *et al*., (1971) suggested that cooling of the face and head results in stimulation of cold receptors on the skin surface and that the concurrent decrease in warm receptor activity would be sufficient to reduce thermoregulatory responses to heat stress.

The effect of head cooling in reducing forearm blood flow, presumably reducing cutaneous blood flow (Roddie *et al*., 1956), may reduce heat flow from the environment to the body, thus reducing heat storage. It might be suggested that general cutaneous vasoconstriction would reduce heat loss via conduction at the skin, thus causing increased heat storage. The results of the present investigation however showed no evidence of increased heat storage with head cooling. In fact, given the environmental conditions (40

°C dry bulb) it is clear that conductive heat loss to the environment would be rendered ineffective and in fact the heat flow would be from environment to body.

Head cooling clearly improved subjective assessment of head, body and overall thermal comfort. Previous investigations have identified the link between thermal discomfort around the head and increased errors made during complex task performance (Allnutt and Allan, 1973; Nunnely *et al*., 1982). Thus, the practical implications of using head cooling in reducing errors made during work in a hot environment are obvious.

Conclusion

Despite the benefits of head cooling demonstrated in these experiments, to incorporate the head cowl into current clothing assemblies for ground crew or industrial workers would present a considerable challenge. The time taken to don the hood and remove it again was a large factor in the design of the current study. Due to these restraints the hood could not be rapidly interchanged and had to remain on the subject's head while not connected to the cooling supply, thereby imposing further heat stress during exercise. It would certainly have been of interest in the current study to add a third bare-headed condition in order to evaluate the added thermal stress of the hood alone.

Potential operational problems associated with water cooling include constant daily use which may lead to water spill, wet clothing, electrical problems and water in the wearer's vision.

Results of this study indicate that head cooling can significantly improve recovery from exercise when made available during the rest periods of brief work/rest cycles. Although the benefits of cooling in improving recovery from work have been identified in these experiments, the effects upon complete recovery from work have not been adequately explored.

The use of head cooling deserves further investigation and development in order to provide a wider range of practical applications both in industry and the military. There will always remain however, a complex trade off between physiological and engineering/technological developments. In the present case, current developments regarding helmet mounted pilot information displays have prevented the implementation of head cooling technology, despite it's obvious benefits for the pilot under heat stress.

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