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EVALUATION OF A PERSONAL COOLING ENSEMBLE USING HUMAN SUBJECTS EXPOSED TO MODERATE AND SEVERE HOT CLIMATIC CONDITIONS

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ABSTRACT

An experimental personal cooling ensemble was evaluated for its ability to cool four subjects exposed to varying degrees of thermal stress. Subjects dressed in complete chemical warfare protective clothing ensembles were exposed to both moderate (29.5 degrees C, 50% R.H.) and severe (35 degrees C, 75% R.H.) hot climatic conditions for 2.5 hours. The experimental sessions consisted of two exposures to each condition; one as control, the second with the personal cooling system. Physiological data recorded throughout the experiment showed that the cooling system was effective in preventing body heat storage under the moderate experimental parameters and that it reduced heat storage by approximately 65% during the more severe conditions. In addition all subjects expressed positive attitudes to the subjective benefits they felt the system provided.

INTRODUCTION

Ambient air temperatures, aerodynamic heating of the air frame, solar radiation and heat generated from avionic components all contribute to the thermal stress encountered in military aviation. These external sources, when coupled with the metabolic heat generated by aircrew themselves can lead to levels of heat stress that seriously affects mental and physical performance. (1)

Under normal conditions, the body dissipates heat through four mechanisms; radiation, conduction, convection and evaporation. The requirement for aircrew to wear multi-layered mission-oriented clothing such as chemical warfare/defence ensembles, immersion suits, anti-G pants, life preservers, partial pressure garmentry, etc., greatly reduces heat dissipation by these processes.

Layered clothing creates insulating barriers that can seriously impede heat loss to the environment. As ambient temperatures exceed body levels, there is a further reduction in the body's ability to remove heat and the mechanisms of radiation, conduction and convection will add to the body's heat build-up. During such conditions, evaporation (accomplished by the process of sweating) becomes the main mechanism for heat loss. Unfortunately with layered clothing, the efficiency of this method is also seriously impeded. Air trapped in layers between the body and clothing may become so saturated with moisture from sweat production that further moisture will not be evaporated for productive heat loss.

In order to circumvent this problem, a system is required to provide cooling beneath such protective clothing. One method of accomplishing this is to circulate a cooled water/glycol mixture through a channelized vest worn close to the skin as a conductive/convection medium for heat exchange. To date considerable work has been carried out to produce a suitable liquid cooling system for use in military aircraft. Presently there is no Air Force in the Western world flying with such an operational unit.

DCIEM initially became involved with liquid cooling several years ago when commercially available units were evaluated in the hopes of finding a system which could be adopted for possible military use (2). Unfortunately, none of those evaluated were entirely suitable for use by aircrew (3). This resulted in work being undertaken by the Medical Life Support Division to produce a viable system which would overcome the problems identified with regard to the design and performance of the commercial units and which at the same time would be acceptable for use in the aviation environment (4).

A prototype system was devised, which showed promising results when subjected to extensive bench testing. In order to evaluate its effectiveness under realistic conditions, it was decided to observe its performance during use by four subjects exposed to simulated degrees of thermal stress. This laboratory study was conducted both to obtain some indication of the system's capability and to identify problem areas which might need corrective action prior to further testing during flight trials. This report documents the experimental results of these laboratory evaluations.

METHODS

The experiments were conducted in the tropical room of DCIEM. A total of five healthy male volunteers (characteristics presented in Table 5) were used throughout the experiment. Four resting subjects were exposed to each of the moderate and severe thermal conditions with and without the experimental cooling system, but always dressed in the same clothing. A complete description of the experimental equipment is provided by Brooks et al (4).

During the moderate exposures which lasted 2.5 hours, the Tropical Room was set at 29.5 degrees C and 50% relative humidity (approximating a WBGT of 26 degrees C). The four subjects were weighed nude prior to commencing the experiment. Skin transducers were attached in four locations; T1 = upper chest, T2 = upper arm, T3 = mid thigh, T4 = calf and ECG leads were attached to monitor cardiac activity. Rectal probe thermometers were inserted into the rectum 15 cm passed the anal margin to measure body core temperature.

The subjects were then dressed in a complete chemical warfare protective clothing ensemble. This consisted of a cotton T-shirt and undershorts, a charcoal impregnated coverall, charcoal socks, CW impervious flying suit, nitrile rubber gloves, leather flying gloves, flight boots, an RAF AR5 CW respirator with filter blower assembly, and the standard Canadian aircrew helmet. In addition a personal cooling vest was worn between the cotton undershirt and charcoal coverall.

The subjects were positioned in the Tropical Room in a seating arrangements simulating those of the CH-124 Sea King helicopter. The cooling vests were connected to the modified DC-10 Accurex chiller supply unit via the manifold system (4). Transducers, rectal probes and ECG leads were connected to recorders. At this point, timing for the experiment began.

ECG recording was continuous. Physiological temperatures were taken automatically every two minutes. Coolant supply and return temperatures were observed throughout the experiment using a Yellow Spring Instrument (YSI) Series 4400 system with thermisters mounted in the chiller supply and return line. The supply temperature was maintained at a steady 16 degrees C throughout the experiment. Upon completion of each 2.5 hour session, subjects were removed from the Tropical Room and reweighed nude.

The second portion of this exposure was conducted two days later to avoid heat adaptation by the subjects. All experimental parameters and procedures were identical to those of the first with the exception that the personal cooling vests were not worn.

A further two days later, the entire process was repeated with the subjects exposed to a more severe thermal condition of 35 degrees C, 75% relative humidity (approximating to a WBGT of 32.5 degrees C), again with and without the benefit of the personal cooling system.

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For all experimental sessions, the protocol required that a subject be removed from the experiment if his core temperature exceeded 39.0 degrees C or if there was a 2 degree C total rise in his core temperature from baseline data. Termination of the experiment also occurred if a subject's heart rate exceeded 145 beats per minute, on the direction of the Medical Observer, or at the subject's request.

RESULTS and DISCUSSION

Body temperatures recorded throughout the experiments were used to calculate mean skin temperatures (Tsk) according to the formula: Tsk = 0.3T1 + 0.3T2 + 0.2T3 + 0.2T4, and mean body temperature (Tb) according to the formula: Tb = 0.67Tre + 0.33 Tsk (Tre = rectal temperature). Tables 1 to 4 present mean skin temperatures and mean body temperatures for pooled subject data. It should be noted that in both exposures without personal cooling, a subject was removed from the experiment before completion of the 2.5 hour test period; therefore, pooled data for these sessions is based on the remaining three subjects.

As indicated by Table 1, there was no significant rise in core temperatures during exposure to the moderate session without personal cooling. There was, however, a substantial increase in mean skin temperatures at the end of the exposure. This resulted in raised mean body temperatures (indicative of heat storage by the body). For resting individuals or individuals engaged in light activity, ideal body temperatures are assumed to be those where core temperatures are <38 degrees C. At this level of activity, skin temperatures are < 34 degrees C with an ideal level of 33 degrees C (5). Once these levels are exceeded, the body rapidly looses its thermoregulatory efficiency. Heat storage may accelerate and cause body temperatures to rapidly reach levels where collapse can occur.

During the moderate exposure, with the benefit of personal cooling, there was only one subject who experienced any rise in temperature (+ .2 degrees C in core temperature after 2.5 hours). Table 2 shows that on average, core temperatures were lower upon completion than the observed starting values. This indicates that, for this degree of thermal loading the cooling system is capable of removing excess heat and even over cooling the body with an inlet temperature of 16 degrees C.

Under the severe condition without personal cooling, both core and skin temperatures were significantly higher at the end of 2.5 hours (Table 3). Thermal loading during this exposure was such that one subject's core temperature did reach 38 degrees C. It can be seen that compared to the moderate exposure, heat build-up during the same time period was approximately doubled (assuming a mean body temperature rise indicates heat gain). During the severe condition exposure with personal cooling, there was still a noticeable increase in both core and skin temperatures (Table 4). Although thermal loading under these conditions was such as to surpass heat removal by the system, the total heat gain as indicated by mean body temperatures was reduced by approximately 65% compared to the case without use of the coolant vests.

During the moderate exposure, weight loss due to sweat secretion was comparable for both the cooled and control sessions (.23 versus .27 kg during the 2.5 hr exposure). In the more severe session, weight loss for subjects averaged approximately .6 kg over the 2.5 hour period without cooling and .4 kg with cooling. (During the severe uncooled session, the weight loss for one subject exceeded 1% of total body weight, i.e. 1.1%). It can thus be seen that even with personal cooling vests, dehydration is still a cause for concern. Similar findings of weight loss while wearing partial coverage cooling garmentry were reported by Edwards & Harrison (7). As they pointed out, in order to overcome problems associated with dehydration, persons should be made aware of the need to remain well hydrated throughout any operations, under hot conditions, even with the benefit of personal cooling vests.

CW clothing was employed during the experiment because it represented the worst case condition which might be encountered during operations in hot climates. This offered the greatest challenge to the cooling system because the majority of heat loss would have to be accomplished through the cooling system. Although conditions were such as to preclude core temperatures from reaching 38 degrees C, it should be emphasized that the data obtained was for resting individuals. With increased metabolic heat production associated with work such as flying (5, 6), there would be a substantial increase in the amount of excess heat generated, causing temperatures to rise more rapidly under similar environmental conditions. Furthermore in the field environment there is the additional heat stress from radiation; this makes conditions even more difficult, however, it was not possible to simulate in this experiment.

One of the more significant outcomes of this experiment was the reconfirmation of earlier results (3) with regards to subjective comfort. All subjects expressed positive attitudes toward the subjective benefits they experienced with the cooling vests. All four subjects completed both sessions involving the vest. One subject was removed from the experiment before its completion in both the controlled cases, once due to discomfort and nausea, the other due to a medical observation (cardiac irregularities).

During the experiment, it became evident that the cooling system had one major shortcoming. There was no individual control of coolant flow to the vest. Coolant liquid was supplied to all four cooling vests at the same inlet temperature of approximately 16 degrees C regardless of the environmental conditions. (There is a control on the chiller to vary the supply temperature through a range from 10 degrees C --> 25 degrees C.) Under the moderdate experimental conditions, this inlet temperature caused some minor overcooling in the resting subjects. This may not have been the case had some form of physical activity increased metabolic heat production.

Work should proceed to incorporate a means of individual temperature selection into the system design over an acceptable temperature range. This feature would allow aircrew utilizing the system to select an inlet temperature commensurate with environmental conditions and personal comfort preferences. It would not be beneficial to lower the coolant temperature in the hopes of improving cooling efficiency since 16 degrees C is about the lowest inlet temperature that should be used for cooling. Lower temperatures tend to produce vasoconstriction of the skin which

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impairs heat transfer from the body to coolant (6). Also when skin temperature decreases to 19 degrees C, a sensation of pain can set in.

Upon completing the incorporation of this remote means of individual temperature control of the coolant into the present configuration, a series of additional laboratory and flight tests should be carried out. These tests should be designed to provide an analysis of the system's effectiveness in alleviating heat storage and providing improved subjective comfort.

SUMMARY

An experimental cooling system was evaluated for efficiency in simultaneously cooling four subjects exposed to varying levels of thermal stress. Experimental results show that the system was capable of removing the majority of body heat build-up and maintaining body temperatures near comfort levels under moderate experimental conditions. During a more severe exposure, the system was useful in reducing body heat build-up by approximately 65%. With the incorporation of a means to provide individual temperature control of coolant, the system should be further evaluated under laboratory and actual flight conditions.

TABLE 1

$\bar{x}$ temperatures ±1 standard deviation for subjects exposed to moderate thermal condition 29.5 degrees C, 50% R.H. without the benefit of a personal cooling vest. N = 3 as one subject voluntarily terminated participation before completion of the 2.5 hour experimental period.

	Start	Finish
$\bar{T}$re (°C)	37.0 ± .20	37.20 ± .27
$\bar{T}$sk (°C)	33.26 ± .93	35.20 ± .36
$\bar{T}$b (°C)	35.80 ± .27	36.57 ± .25

TABLE 2

$\bar{x}$ temperature ±1 standard deviation for subjects exposed to moderate thermal condition 29.5 degrees C, 50% R.H. with benefit of personal] cooling vest. N = 4.

	Start	Finish
$\bar{T}$re (°C)	37.23 ± .17	36.82 ± .42
$\bar{T}$sk (°C)	34.85 ± .40	35.20 ±1.63
$\bar{T}$b (°C)	36.38 ± .21	35.47 ± .66

TABLE 3

$\bar{x}$ temperatures ±1 standard deviation for subjects exposed to severe thermal condition 35 degrees C, 75% R.H. without the benefit of a per- sonal cooling vest. N = 3 as one subject's participation was ter- minated before completion of the 2.5 hour experimental period.

	Start	Finish
$\bar{T}$re (°C)	37.10 ± .17	37.67 ± .42
$\bar{T}$sk (°C)	33.87 ± .91	36.90 ± .30
$\bar{T}$b (°C)	36.03 ± .21	37.47 ± .31

TABLE 4

$\bar{x}$ temperatures ±1 standard deviation for subjects exposed to severe thermal conditions 35 degrees C, 75% R.H. with benefit of personal cooling vest. N = 4.

	Start	Finish
$\bar{T}$re (°C)	37.18 ± .15	37.55 ± .13
$\bar{T}$sk (°C)	34.98 ± .21	35.75 ± .47
$\bar{T}$b (°C)	36.48 ± .09	36.98 ± .22

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TABLE 5

Subject	Age	Weight (kg) Nude	Height (cm)
1	38	69.0	168.5
2	24	79.3	176
3	34	75.3	178
4	23	77.3	176
* 5	28	68.3	175

* Subject No. 5 replaced Subject No. 4 for the severe experimental exposure.

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