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ABSTRACT

The purpose of this investigation was to determine if cooling the feet is as effective as cooling the hands in the alleviation of heat stress. Each of six volunteers dressed in chemical warfare (CW) protective clothing, sat for 120 min in an environment of 35°C and then immersed his feet in a water calorimeter for 20 min. Heat lost to the calorimeter was measured at water temperatures of 10, 15, 20, 25 and 30°C. The use of water-cooled socks was also examined under these environmental conditions. It was found that heat loss from the feet was comparable to that from the hands, indicating that the two methods are equally efficient. Preliminary results indicate that the use of water-cooled socks may also be practical.

RÉSUMÉ

Le but de cette enquête était de déterminer si le refroidissement des pieds est aussi efficace que le refroidissement des mains pour alléger le stress thermique. Chacun des six volontaires habillés de l'ensemble de protection chimique, s'assirent pour 120 minutes dans un environnement de 35°C et puis immergèrent leurs pieds dans un calorimètre à eau pour 20 minutes. La chaleur perdue au calorimètre fut mesurée à 10, 15, 20, 25 et 30°C. L'utilisation de bas refroidis par eau fut également examiné sous ces mêmes conditions environnementales. On a trouvé que la chaleur perdue par les pieds était comparable à celle par perdue par les mains, indiquant que les deux méthodes sont aussi efficaces. Les résultats préléminaires indiquent que l'utilisation de bas refroidis par eau peut aussi être pratique.

EXECUTIVE SUMMARY

Hyperthermia (increase in body temperature due to heat stress) has long been recognized as a problem in various trades in the Canadian Forces. It has been found that immersing the hands in cool water will increase the loss of body heat by as much as 100 watts. This method of cooling, however, is impractical because when the hands are being cooled they cannot be used to perform their various tasks.

In this study the effect of cooling the feet on body heat content was examined as another means of cooling the body. Each of six volunteers dressed in winter underwear, woollen socks, combat boots, CW coveralls and impermeable gloves and then entered an environmental chamber at 35°C. After sitting for 120 minutes, his socks and boots were removed and his feet immersed in a water bath for 20 minutes. This procedure was repeated at bath temperatures of 10, 15, 20, 25 and 30°C. Additional experiments utilizing water-cooled socks instead of the water calorimeter were also conducted.

As would be expected, more heat was lost from the feet as the water temperature decreased. More than 100 watts can be removed from the body using this technique. This indicated that foot immersion was as effective as, and perhaps more effective than, hand immersion as a method of reducing body heat. Water-cooled socks were found to have potential use as a means of cooling personnel in static situations.

INTRODUCTION

Hyperthermia may occur in circumstances where individuals are obliged to wear clothing which provides excessive thermal insulation or must operate in hot environments. Its prevention has been a concern of the Canadian Forces (CF) for many years. Recent experiments (Livingstone et al., 1989) have shown that the immersion of the hands in cool water is an effective means of removing heat from the body when one is working in situations which might induce hyperthermia.

Since cooling the hands by immersion in water or by any other means effectively inhibits their use, cooling the body via the hands is not always practical. However, there are certain static or semi-static situations in the CF (members of tank crews or helicopter pilots on stand-by, for example) where restricting the feet does not affect performance. In such cases it might be possible to reduce heat stress by cooling the feet without hindering performance. The current study was performed to determine whether cooling the feet would be as effective as cooling the hands in alleviating heat stress.

METHODS

Six members of the DREO test team volunteered to act as subjects for our investigation. Their anthropometric characteristics are given in Table 1.

TABLE 1

Anthropometric characteristics of test subjects

Subject	Age (yr)	Height (cm)	Weight (kg)
1	24	167	78
2	25	185	74
3	26	170	75
4	29	168	54
5	24	178	67
6	23	182	86

A small, commercially-available, 30 L insulated picnic cooler was used as a water calorimeter to measure the amount of heat removed from the body via the feet. After being filled with 24 L of water, a Lauda Model T-1 circulating pump was used to stir the water constantly to ensure equal temperature distribution in the calorimeter. In order to measure the water temperature, thermistors were placed near the top, middle and bottom of the cooler. Preliminary experiments were done to determine the temperature characteristics of the calorimeter.

Each subject donned winter underwear, CW protective clothing, woolen socks and combat boots after which he entered an environmental chamber set at 35°C. He then sat in an upright chair for a period of 120 minutes after which his boots and socks were removed, his underwear and pant legs rolled up to his knees and both feet were immersed in the water calorimeter for a period of 20 minutes. During each experiment, the temperature of the water in the calorimeter was measured and recorded every 20 seconds. The subjects repeated the procedure on different days at water temperatures of 10, 15, 20, 25 and 30°C.

The amount of heat transferred from the feet to the calorimeter was determined for all cases using the following equation:

$$Q = mct^{-1} (T_f - T_i - k) \ W$$

where

m = mass of water (g)
c = specific heat of water (J/g°C)
t = time (s)
T_i = water temperature when feet immersed (°C)
T_f = water temperature when feet removed (°C)
k = change in water temperature when feet not immersed (°C)

Since $m = 2.4 \times 10^4$ g, $c = 4.2$ J, and $t = 1.2 \times 10^3$ s, the total amount of heat transferred from the feet to the calorimeter during each experiment was:

$$83.7 (T_f - T_i - k) \ W$$

Changes in the surface temperatures of the legs below the knees and above the water level were examined during the immersion using an infrared thermography system (AGA 680).

Analysis of variance was performed on the changes in body heat loss caused by foot immersion in the calorimeter using the method described in Snedecor and Cochran (1980).

Since immersing the bare feet in water in a military situation is not realistic, the manufacturer of whole-body cooling suits (Exotemp Ltd, Pembroke, Ontario) was contracted to design and construct prototype socks and insoles which could be used to cool the feet. These can be worn inside military footwear and consist of two parallel circuits of approximately 10 m of 1.5 mm inner diameter tygon tubing, spaced about 10 mm apart and sewn to the inside of calf-length Lycra socks. This ensemble was connected to an insulated reservoir containing about 20 L of cold water which was circulated through the tubing at approximately 100 ml/minute by a variable-speed electric pump.

Further experiments using this footwear were performed. As above, the subjects dressed in their protective clothing plus the cooling socks and insoles and entered the environmental chamber at 35°C. Instead of removing the footwear and immersing bare feet in the water calorimeter at the end of 120 minutes in the chamber, the cooling unit's pump was turned on and cold water was circulated through the socks on each foot for a period of 20 minutes. No temperatures were measured.

RESULTS

The results of the experiments are shown in Figs 1 to 3 and Table 2. Only five values were obtained for the lowest water temperature because one of the subjects could not complete the experiment. The amount of heat transferred from the feet to the calorimeter at various water temperatures during the experiments was comparable to results obtained during our investigation of heat loss via the hands (Livingstone et al., 1989). As before, the quantity of heat lost increased as the water temperature decreased.

TABLE 2

Heat lost to water bath via the feet.

Temperature (°C)	Heat Loss (watts ± S.E.)
10	151 ± 15 *
15	91 ± 12 #
20	84 ± 13
25	82 ± 8
30	55 ± 5

* significantly different from other values at 1% level
# significantly different from 30°C value at 5% level

Straight line equation: $y = -3.86x + 169.24$

where: y is heat loss (watts)
x is water temperature (°C)

During the thermographic studies of these experiments, the feet were seen to be uniformly warm initially (Fig 2a). However, several minutes after immersing the feet in the water the peripheral blood vessels became clearly delineated, evidenced by the dark lines (Fig 2b, 2c) which indicate a cooler surface area caused by cool blood flowing up the superficial veins of the leg. Fig 3 is a thermograph of the right leg of one of the subjects taken several minutes after his feet were placed in the water. The areas adjacent to the veins appear darker, indicating an apparently well-established blood flow cooling the surrounding tissue as well as cooling the body core.

The subjective results from the experiments in which the water-cooled socks were worn also indicated that this method of cooling showed promise. During the two-hour period at 35°C, all subjects felt uncomfortable and perspired profusely. When the cool water began to circulate through the socks, the subjects immediately felt more comfortable and claimed to have stopped sweating. One of the subjects, a helicopter pilot, felt that cooling using the socks would be feasible while flying a helicopter.

DISCUSSION

These results indicate that the removal of body heat via the feet is comparable to that from the hands, indicating that the two methods are equally efficient. Under the conditions of our experiments, it was seen that blood flowing from the feet to the body does so via the superficial veins of the legs. This supports the hypothesis of Vanggaard (1975) who has postulated that blood flows directly to the heart via the superficial veins rather than returning to the core via the central veins. Thus, cooling the blood in the extremities is effective in lowering the temperature of the body core. This statement is in direct contrast with, but does not repudiate, the long held theory of countercurrent heat exchange in which it is believed that the body is able to control heat loss or gain from the environment by means of heat exchange between the central arteries and veins in the leg. However, if this is valid we would see a gradual cooling from the foot to the body when the feet are immersed in cool water and vice versa. Instead, our results indicate that at least a portion of the blood is returning through the superficial veins.

We have shown that more than 100 watts of heat may be removed from the body simply by immersing the feet in cool water. This amount is slightly more than the amount of heat loss when the hands were immersed in cool water (Livingstone et al., 1989) indicating that this method of cooling is as effective as cooling the hands. Although the quantity of heat lost when water-cooled socks were worn was not measured, it is felt that this is a feasible method of cooling heat-stressed individuals.

Although this method of cooling may be difficult to apply to military personel in mobile situations, it may be useful in increasing heat loss in those in static or semi-static situations such as pilots, tank personnel and others whose hands must be free to remain operative. Further investigations are being planned to determine if the bulky and heavy water cooler and pump can be replaced by a much smaller water source and a light portable power supply so as to make the system more portable.

CONCLUSION

It was found that immersing the feet in cool water was a feasible means of alleviating heat stress in individuals dressed in CW clothing sitting in an environment of 35°C.

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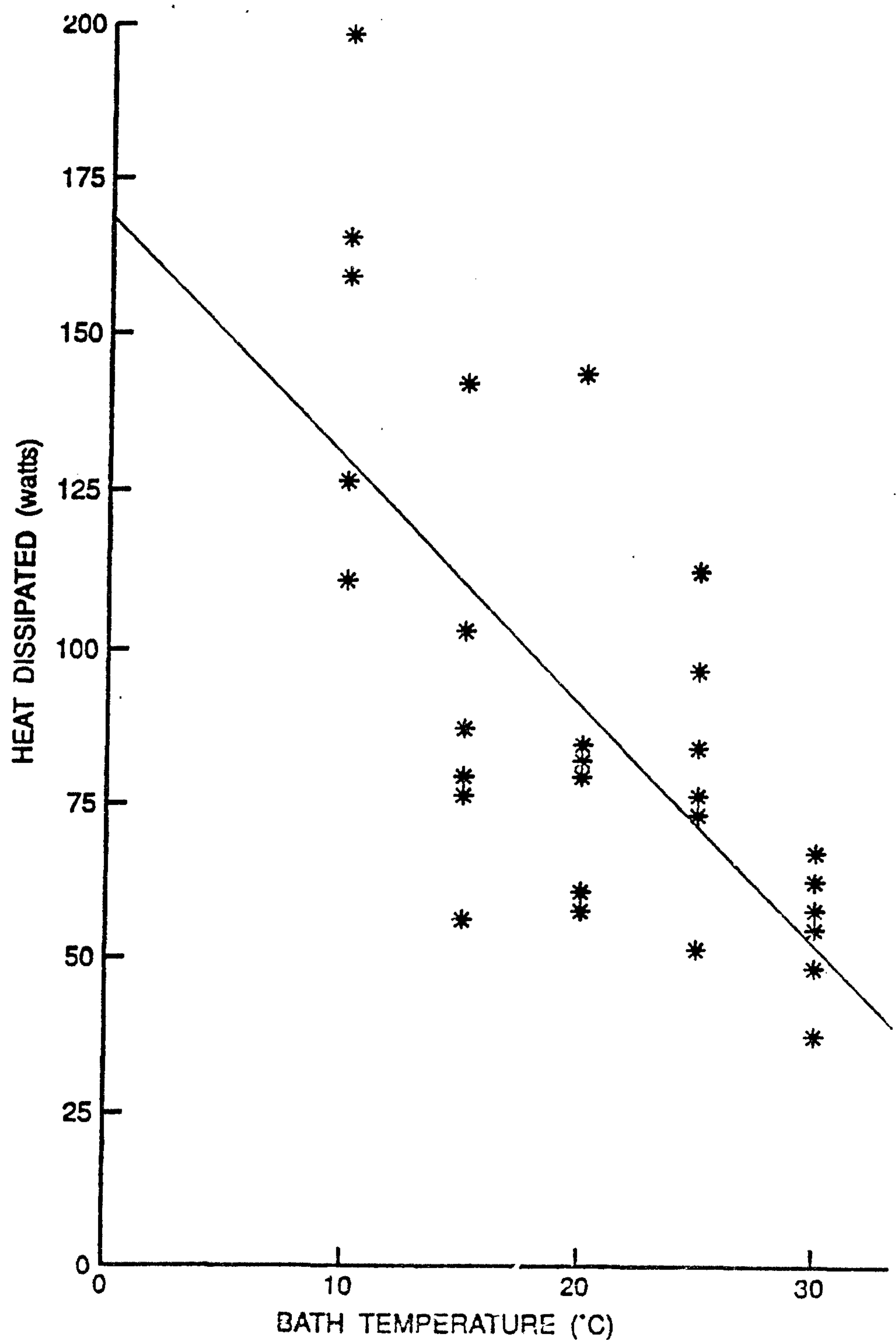

Figure 1: Heat loss from the feet immersed in water at various temperatures.

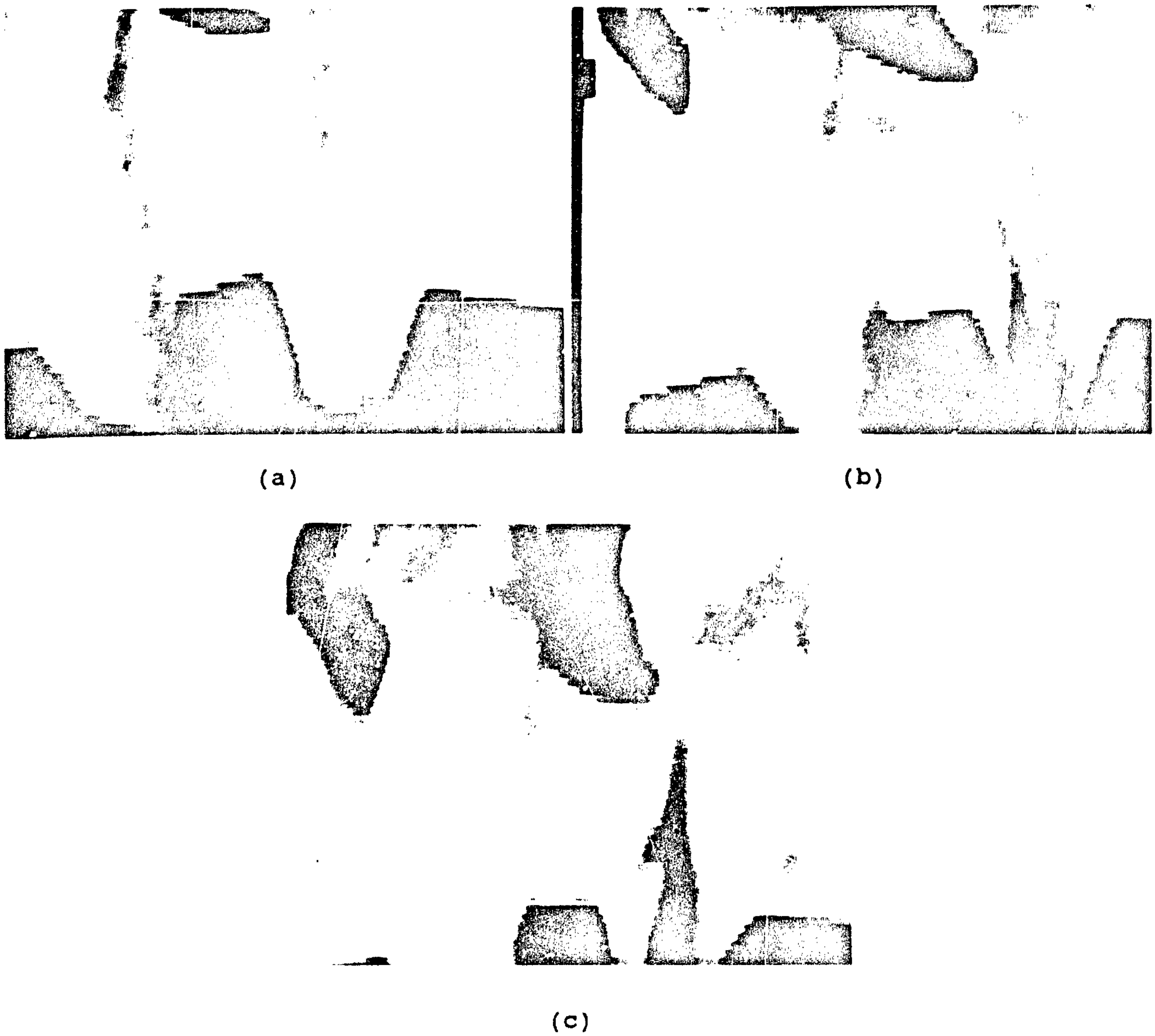

Fig 2. Thermograms of the legs of a subject after feet were placed in calorimeter. The thermogram is set in the white-hot mode i.e. the whiter the colour the warmer the temperature. The thermograms show the initial temperature distribution of the legs immediately after entering the water (2a), two minutes after immersion (2b) where it can be seen that a cool area has appeared on the calf of the left leg just above the bath, and six minutes after immersion (2c) where the cool area has progressed up the leg giving a wider and more definite dark pattern.

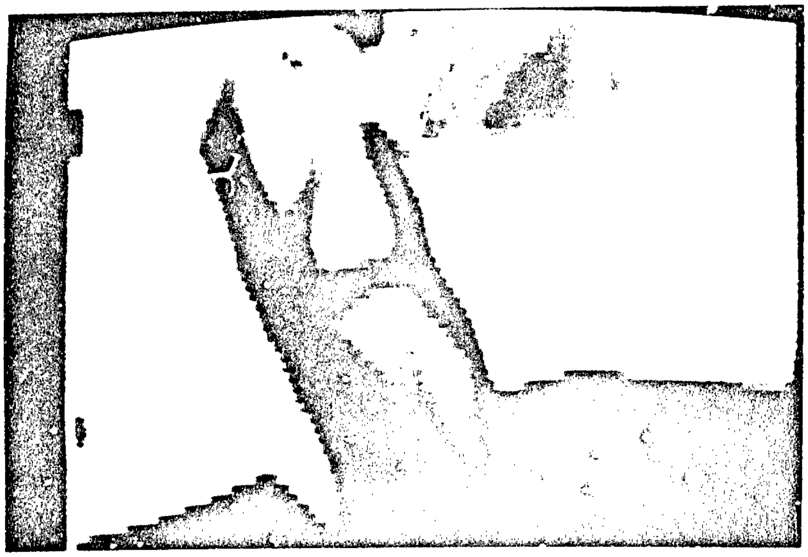

Fig 3. Thermogram of the right leg approximately 15 min after immersion in calorimeter. The thermogram is in the white-hot mode. The dark areas on the leg can be recognized readily as a venous pattern. It can also be seen that the cool areas are larger than the veins showing that the tissue around the vein is being cooled.

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