Cooling hyperthermic firefighters by immersing forearms and hands in 10°C and 20°C water

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RESEARCH ARTICLE

Cooling Hyperthermic Firefighters by Immersing Forearms and Hands in 10°C and 20°C Water

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Introduction: Firefighters experience significant heat stress while working with heavy gear in a hot, humid environment. This study compared the cooling effectiveness of immersing the forearms and hands in 10 and 20°C water. ***Methods:*** Six men (33 ± 10 yr; 180 ± 4 cm; 78 ± 9 kg; 19 ± 5% body fat) wore firefighter 'turn-out gear' (heavy clothing and breathing apparatus weighing 27 kg) in a protocol including three 20-min exercise bouts (step test, 78 W, 40°C air, 40% RH) each followed by a 20-min rest/cooling (21°C air); i.e., 60 min of exercise, 60 min of cooling. Turn-out gear was removed during rest/cooling periods and subjects either rested (Control), immersed their hands in 10 or 20°C water (H-10, H-20), or immersed their hands and forearms in 10 or 20°C water (HF-10, HF-20). ***Results:*** In 20°C water, hand immersion did not reduce core temperature compared with Control; however, including forearm immersion decreased core temperature below Control values after both the second and final exercise periods ($p < 0.001$). In 10°C water, adding forearm with hand immersion produced a lower core temperature (0.8°C above baseline) than all other conditions (1.1 to 1.4°C above baseline) after the final exercise period ($p < 0.001$). Sweat loss during Control (1458 g) was greater than all active cooling protocols (1146 g) ($p < 0.001$), which were not different from each other. ***Discussion:*** Hand and forearm immersion in cool water is simple, reduces heat strain, and may increase work performance in a hot, humid environment. With 20°C water, forearms should be immersed with the hands to be effective. At lower water temperatures, forearm and/or hand immersion will be effective, although forearm immersion will decrease core temperature further.

Keywords: heat stress, hyperthermia, vapor barrier, thermoregulation, heat illness, heat stroke.

MANY COMMERCIAL, industrial, and military operations expose participants to significant heat stress. Prevention of hyperthermia and heat illness while working in dangerous conditions with high environmental temperatures is critical, as a rise in core temperature can limit work output (23), impair cognitive ability and behavior, and increase the risk of accidents (7). During heavy work in the heat, the body may experience increasing heat gain if the effects of raised metabolic heat production from work, exercise, and high environmental temperature are not counteracted. Normally, this increased heat gain is balanced by heat loss mechanisms such as evaporation of sweat, conduction, convection, and/or radiation.

Firefighters (turn-out gear), military personnel (nuclear biological chemical protective suits), engine room personnel, or other industrial workers wear protective clothing which is often several layers thick, bulky due to high insulation and fire retardant properties, and may also be vapor impermeable. Although this clothing provides protection from high environmental temperatures, it may prevent the dissipation of metabolic heat (22) through all heat loss mechanisms (1,16,21,22). Consequently, over time, the body will gradually store heat and core temperature may increase.

In order to prevent hyperthermia, garments containing phase-change materials or cooled liquid, ice, gas, and air have typically been used to cool the torso, attenuating the rise in core temperature while protective clothing is worn (9,17,24,32,33). The effectiveness of any cooling procedure is dependant on: 1) the percentage of the body surface area that is cooled; 2) the temperature gradient between the skin and the cooling medium; and 3) the amount of blood flow to the actively cooled skin. Normally skin blood flow will be very high when core temperature is raised during exercise (26).

Distal limb immersion in cool water has also been proposed as a viable cooling option. The hands and forearms could act as a heat exchanger, which is dependant on peripheral vasodilation. Warm blood is cooled and heat is dissipated to the surrounding water through convection and conduction. This principle has been partially evaluated in studies involving hand-only cooling in subjects wearing chemical protective or firefighting gear and exercising in 23 to 40°C air. Cooling was accomplished by immersion of the gloved (1,21) or naked (16) hands in 0 to 30°C water, either during exercise in the heat or during rest periods. In general, hand immersion attenuated or reversed the development of hyperthermia and/or increased work capacity, with cooling being more effective at lower water bath temperatures and if the hands were uninsulated. Importantly, hand immersion in water as cold as 0°C did not induce vasoconstriction (1,16,17,21) to an extent that

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would limit blood flow through the hand and subsequently limit heat loss (19).

It is of interest whether additionally immersing the forearms would enhance core cooling. Since the forearms have a greater proportion of total body surface area (~7%) than the hands (~5%) (20), their additional immersion could be beneficial. Vanggaard and Gjerlof (30) first proposed immersion of forearms, and the hands, in warm water as an effective method for rewarming cold-stressed individuals. Forearm and hand immersion in 45°C water rapidly reversed vasoconstriction and initiated rapid core warming (29). It is not known, however, whether forearm immersion would augment core cooling of hyperthermic individuals. Since vasoconstriction is controlled in response to an integrated thermal signal from skin and core thermoreceptors (2,6), additional cooling of the forearm could induce vasoconstriction and reduce heat loss (19).

The effect of forearm immersion is an important practical question for firefighters as cool/cold water is normally readily available at firefighting sites. Firefighters can remove their heavy jackets during rest periods and they can easily include the forearms with the hands during immersion. This may provide a practical advantage for offsetting heat strain, increasing worker safety, and potentially reducing recovery times. The purpose of the present study was to determine the effectiveness of including the forearms, along with the hands, during cool- and cold-water immersion for cooling heat stressed subjects. It was hypothesized that hand and forearm immersion would cause greater heat loss and core cooling than hand-only immersion, and that immersion in 10°C water would not induce vasoconstriction, thus increasing heat loss and core cooling compared with 20°C water.

METHODS

Subjects

The experimental protocol was approved by the Education/Nursing Research Ethics Board at the University of Manitoba. Six men [(mean ± SD) 32.5 ± 10 yr old, 179.7 ± 4 cm tall, mass 77.5 ± 9 kg, body surface area of 1.96 ± 0.1 m^2, and body fat of 19.4 ± 5%], provided written, informed consent for the study. The study was open to men and women, however, only men volunteered for the study. Subjects were in good physical condition and free of any known diseases (determined through a PAR-Q questionnaire). Height, weight, age, underwater weight, and four measurements of skin fold thickness were determined and percent body fat was calculated from estimates of body density (11) and skinfold thickness (4).

Instrumentation

Although esophageal temperature is a commonly used measure of core temperature (8), pilot studies demonstrated this technique was not practical because frequent water ingestion during the trials invalidated esophageal temperature measurements. Therefore, aural canal temperature (T_{ac}) was measured with a cotton tipped-tympanic thermocouple (Mallinckrodt Medical Inc., St. Louis, MO) inserted into the auditory canal near the tympanic membrane. Subjects were asked to slowly insert the thermocouple into the auditory canal until they felt slight discomfort or pain, which indicated contact with the tympanic membrane, and then retract the probe just enough to relieve the discomfort. The probe was secured with tape, the auditory canal was occluded with a cotton ball, and a thermally insulated ear cover was placed over the ear to prevent thermal contamination from the environment. When proper care is taken to insulate the external ear, aural canal temperature provides an acceptable indication of changes in core temperature (15,27,31). Single-channel electrocardiogram and heart rate were also monitored.

Cutaneous heat flux ($W \cdot m^{-2}$) and skin temperature (°C) were measured from seven sites on the hands and arms using thermal flux transducers (Concept Engineering, Old Saybrook, CT) according to standard procedures (20). Body surface area (BSA) was calculated as follows: area (m^2) = $\text{weight}^{0.425}$ (kg) · $\text{height}^{0.725}$ (cm) · 0.007184 (10). The following regional percentages were assigned based on Layton et al. (20): fingers 2.5%, dorsum of the hand 1.25%, anterior hand 1.25%, anterior forearm 3.5%, posterior forearm 3.5%, anterior upper arm 3.5%, and posterior upper arm 3.5%. Flux was defined as positive when heat traversed the skin toward the environment (i.e., heat loss) and values for each transducer ($W \cdot m^{-2}$) were converted into $W \cdot \text{region}^{-1}$ as previously described (29). All data were recorded at 30-s intervals.

Total sweat loss was calculated for each trial based on the net change in body mass. The mass of sweat was calculated instead of volume because sweat was not sampled and evaluated for its specific gravity; a value that might change throughout the trial. Body mass was determined before and immediately following completion of each trial. The subject's underclothing was weighed just prior to the initial body mass measurement and just after the final body mass measurement. Volume and mass of water consumed and urine output (if any) were also recorded.

Total sweat loss was calculated as follows: $m_{\text{sweat loss}} = (m_{\text{body i}} - m_{\text{clothes i}}) + m_{\text{water}} - m_{\text{urine}} - (m_{\text{body f}} - m_{\text{clothes}})$, where $m_{\text{sweat loss}}$ is the mass of sweat lost during the entire protocol, m_{body} is the mass of the subject and underclothes, m_{clothes} is the mass of the underclothes, m_{water} is mass of ingested water, and i and f refer to initial and final measurements.

In order to ensure proper hydration status prior to participating in each trial, urine specific gravity (USG) was determined. On arrival at the laboratory subjects provided a urine sample and a reagent strip was used to determine USG. A USG value equal to or less than 1.020 indicates minimal dehydration (18), and this criterion was required before proceeding with the trial. If the USG value was 1.021 or greater, subjects drank 2–3 cups of water and a second test was performed after approximately 1 h. If necessary, this procedure was repeated until the USG reached the inclusion criterion.

Protocol

Subjects participated in five trials, each involving three 20-min exercise bouts followed by 20 min of rest with either no active cooling or four different cooling conditions. The order of the conditions was randomly assigned to achieve a balanced design. On occasion, two subjects participated at the same time, although their cooling conditions were not necessarily the same.

Each subject performed their trials at the same time of the day to control for circadian effects. They were asked to refrain from smoking, consuming alcohol, and performing moderate-to-heavy exercise within 24 h before each trial. They were also asked to drink 2–3 glasses of water and eat a moderately sized meal no less than 1–2 h prior to arrival. A urine sample was colleted immediately on arrival for each trial for the analysis of USG.

In each trial subjects wore the same clothing ensemble consisting of cotton pants, socks, and a short sleeve t-shirt. Before subjects began exercising, they sat in an ambient temperature of 21°C while 10 min of baseline data were collected. They then donned the firefighting 'turn-out' clothing, which consisted of a jacket, pants, rubber boots, thermoclava, helmet, and a self-contained breathing apparatus (SCBA), including an empty air tank (total weight of turn-out gear was 27.3 kg). The jacket and pants are composed of an outer fire retardant layer, a middle layer of quilted insulation, and an inner layer of Gore-Tex.

Subjects then entered an environmental chamber, set at 40°C and 40% RH, and performed three successive bouts of 20 min of stepping exercise and 20 min of rest/cooling (i.e., 60 min each of exercise and rest). Each exercise bout was comprised of a step test with a step height of 22.5 cm and a rate of 20 steps $\cdot$ min^{-1}. Based on a mean body mass of 77 kg (range 67.3 to 87 kg) and 27.3 kg of equipment, the external work rate was 78 W (range 71 to 85.5 W).

After each exercise bout, subjects exited the environmental chamber into the laboratory (ambient temperature 21°C) and removed their jacket, gloves, helmet, SCBA, and thermoclava. They then stood beside a large temperature-controlled water tank (8,300 L) and performed one of the following: 1) no hand or forearm immersion (Control); 2) hand-only immersion in 20°C water (H-20); 3) hand and forearm immersion in 20°C water (HF-20); 4) hand-only immersion in 10°C water (H-10); or 5) hand and forearm immersion in 10°C water (HF-10). Hand immersion consisted of placing the hands in a water bath up to the wrist, while hand and forearm immersion included immersion up to the elbow. The large water tank was used to provide a constant heat sink as water temperature was controlled to ± 0.1°C.

Subjects rested in the relatively cool ambient temperature because firefighters would normally exit the work environment for recovery periods. Clothing and SCBA were removed in all conditions, including Control, in order to maintain a constant passive cooling component for every condition. Removal of this equipment would also be a normal procedure in the field, especially in the absence of active cooling measures. Thus every condition included passive cooling.

Following the first rest/cooling period, subjects redonned their turn-out gear, entered the environmental chamber, and repeated the exercise/rest bout two more times. There were 2-min transition periods following each exercise and rest/cooling period to allow for doffing or donning the clothing, moving between the environmental chamber and laboratory, and drinking water. Subjects normally drank 250 ml of 21°C water after USG determination but before baseline. They also drank 350 ml of water during the 2-min transitions following each exercise period. The protocol dictated that trials would terminate if either the core temperature increased to 39°C (or 2.0°C above baseline), the subject wished to stop, or the investigator(s) terminated the trial.

Data Analysis

Results are reported as means ± SD. For each condition, the total heat loss (kJ) from the upper arm, forearm, and hand were calculated for the 60 min of rest/cooling. Changes in core temperature were calculated as follows. For each 20-min exercise period, warming rates were calculated from the linear increase in core temperature (i.e., from min 5 to 20), and the duration and amount of the after-rise was determined. The after-rise period included the time following exercise termination, when the core temperature continued to rise and lasted until it returned to the end-exercise value (see **Fig. 1**); after-rise amount was the difference between T_{ac} at end-exercise and its zenith. During the 20-min rest/cooling periods there was a definite inflection in the progression of core temperature as the rate of cooling decreased. Thus the initial cooling rate for each rest/cooling period was calculated from the time that core temperature started to decline until minute 10. The secondary cooling rate was calculated from minutes 11–20. The amount and duration of the after-drop period was also calculated for the period in which core temperature continued to decrease and lasted until it returned to the end rest/cooling value. After-drop amount was the difference between T_{ac} at end rest/cooling and its nadir.

Data for the five conditions were compared using repeated measures analysis of variance. Tukey's test was used for post hoc analysis of significant differences with $p < 0.05$. A paired *t*-test was used for pre-post comparisons and to compare initial and secondary cooling rates.

RESULTS

There were no differences between conditions after the first 30 min as T_{ac} increased from baseline values of 36.8 ± 0.1°C, to 37.8 ± 0.1°C at the end of the first exercise period (Fig. 1). By the end of the second exercise period T_{ac} was higher in Control (1 ± 0.24°C above baseline) than all conditions except H-20 ($p < 0.01$) and T_{ac} was lower in HF-10 (0.92 ± 0.2°C above baseline) than in Control and H-20 conditions ($p < 0.01$). At the end of the third exercise period T_{ac} was higher in Control (1.4 ± 0.2°C above baseline) than all conditions except H-20 ($p < 0.01$) and T_{ac} was lower in HF-10

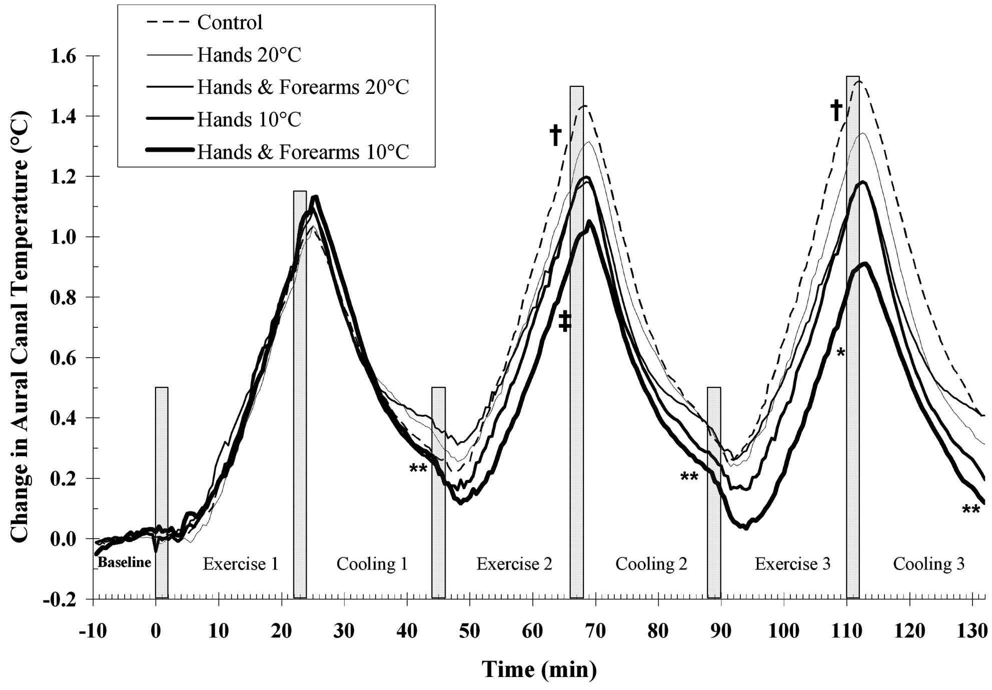

Fig. 1. Aural canal temperature for five conditions during three bouts of 20-min exercise and 20 min of rest/cooling (exercise conditions, 40°C air with 40% RH; rest/cooling conditions, 21°C air) (n = 6). * HF-10 lower than all other conditions ($p < 0.001$). ‡ HF-10 less than Control and H-20 conditions ($p < 0.01$). † Control greater than all conditions except H-20 ($p < 0.01$). ** All conditions, except HF-10, greater than baseline values ($p < 0.001$). Vertical bars indicate 2-min transition periods. Note the after-rise period includes the time following exercise termination, when the core temperature continues to rise until it returns to the end-exercise value. Likewise, the after-drop period includes the time following rest/cooling termination, when core temperature continues to decrease until it returns to the end rest/cooling value.

(0.8 ± 0.2°C above baseline) than all other conditions ($p < 0.001$). At the end of all three rest/cooling periods, T_{ac} was higher than baseline in all conditions (average of 0.3°C above baseline) ($p < 0.001$) except for HF-10, which was not significantly above baseline values.

At the end of each exercise bout, T_{ac} transiently continued to increase throughout the first portion of the subsequent cooling period (i.e., after-rise). Within each condition, the after-rise duration decreased from the first recovery period (7.4 ± 2.6 min) to the second (5.3 ± 1.4 min) and third (5.3 ± 1.6 min) exercise periods ($p < 0.02$). Although there was also a tendency in each condition for the after-rise amount to decrease from the first to the second and third recovery periods, the decrease was only significant in the HF-10 condition (i.e., decreasing from 0.27 ± 0.2 to 0.14 ± 0.1°C) ($p < 0.01$).

At the end of each cooling period, T_{ac} transiently continued to decrease throughout the first portion of the subsequent exercise periods (i.e., after-drop). This after-drop tended to be greatest in the HF-10 condition. After-drop duration was longer in HF-10 than all other conditions following both the first (11.2 ± 3.9 vs. 7.3 ± 3.3 min, respectively) and second (12.3 ± 3.0 vs. 8.3 ± 2.6 min) rest/cooling periods ($p < 0.01$) while the after-drop amount was greater in the HF-10 condition (0.29 ± 0.2°C) than all other conditions (0.14 ± 0.02°C) only following the second rest/cooling period ($p < 0.05$).

In all three rest/cooling periods, the core cooling rate consistently decreased after 10 min in each condition (initial cooling rates ranging from 3.1 ± 1.4 to 4.7 ± $2.0°C \cdot h^{-1}$; secondary cooling rates ranging from 0.9 ± 0.5 to 2.5 ± $0.3°C \cdot h^{-1}$) ($p < 0.05$). There were no differences between conditions in the attenuation of the cooling rates after 10 min of cooling; cooling rate attenuations ranged from 1.4 ± 1.1 to 2.9 ± $1.9°C \cdot h^{-1}$.

Mean skin temperature of the whole arm was initially similar in all conditions, rising from 32.2 ± 0.5°C at baseline to 36.8 ± 0.3°C at the end of the first exercise period. At the end of the second exercise period, mean arm temperatures ranged from 37.3 ± 0.7°C (Control) to 35.2 ± 1.2°C (HF-10). At the end of each cooling period, mean total arm temperatures in all conditions were significantly different from each other (Control, 32.9 ± 0.8°C; H-20, 26.0 ± 1.2°C; HF-20, 23.4 ± 1.4°C; H-10, 21.4 ± 0.5°C; and HF-10, 17.0 ± 0.6°C; $p < 0.001$).

Total hand heat loss over three 20-min rest/cooling periods was greater in all active cooling conditions (177 ± 23 kJ) compared with Control (47 ± 7 kJ) ($p < 0.001$), with values being greater in H-10 than HF-20 ($p < 0.001$; **Fig. 2**). Forearm heat loss was greater in both HF conditions than the hands-only conditions, with values being greater in the HF-10 vs. HF-20 condition (268 ± 46 and 188 ± 35 kJ, respectively) ($p < 0.001$). Upper arm heat loss was similar in all conditions (58 ± 5 kJ).

There were no significant differences in heart rate at any time between any of the conditions. Baseline heart rate was 75 ± 7 bpm. Heart rate increased steadily throughout exercise to 133 ± 4, 139 ± 5, and 142 ± 6 bpm at the end of exercise periods 1, 2, and 3, respectively. Heart rate decreased to 81 ± 3, 80 ± 5, and 79 ± 3 bpm at the end of rest/cooling periods 1, 2, and 3, respectively.

Subjects were euhydrated before starting all trials (mean USG = 1.015 ± 0.003) and there were no significant increases in USG following any condition. Each subject drank 1.3 L of water during each trial; one subject drank 1.2 L during HF-10 and one subject drank 1.55 L during Control. None of the subjects had to urinate during any condition except during a transition period of one trial in the HF-10 condition (urine volume = 50 ml). Sweat loss was greater during Control (1458 ± 270 g) than the other conditions (H-20 = 1192 ± 170 g; HF-20 = 1158 ± 206 g; H-10 = 1117 ± 194 g; and HF-10 = 1117 ± 284 g) ($p < 0.001$).

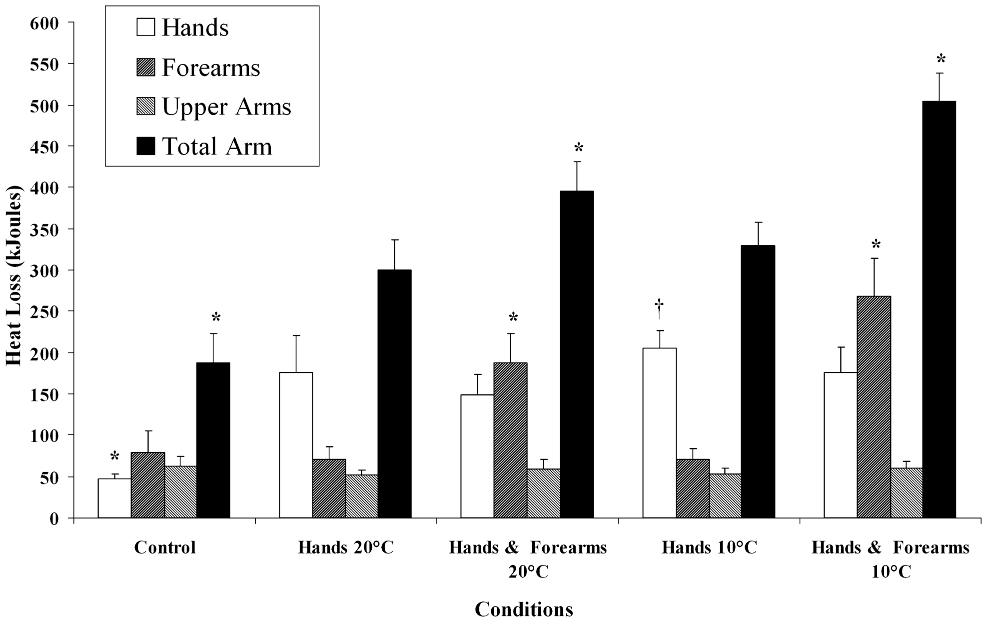

Fig. 2. Total heat loss from the hand, forearm, upper and total arm during 60-min of rest/cooling periods for five conditions (n = 6). * Different from all other conditions ($p < 0.001$). † Greater than HF-20 ($p < 0.001$).

DISCUSSION

This study compared the effectiveness of four cool/cold water hand- and/or forearm-immersion protocols for reducing the heat strain on men working at a moderate rate while wearing full firefighter turn-out gear in a hot, humid environment. A novel aspect of this study was the addition of forearms to the traditional hand immersion protocol. In both 20°C and 10°C water, additional forearm immersion resulted in lower core temperature during exercise than hand immersion only.

In 20°C water, hand immersion did not reduce core temperature compared with passive cooling during Control conditions. Additional forearm immersion in 20°C water increased heat loss by 117 kJ (60 min of cooling) and reduced core temperature during exercise compared with control. Immersing the hands and forearms in 10°C water was the most effective protocol. In this condition, forearm immersion increased heat loss by 197 kJ. This produced a lower core temperature (0.8°C above baseline) than all other conditions (1.1 to 1.4°C above baseline) after the final exercise period and was the only protocol to return core temperature to baseline levels after each of the three cooling periods. Compared with the Control condition, active cooling decreased sweat loss by one-quarter to one-third of a liter.

Hand immersion in cool water is a viable cooling option for heat stress. Livingstone et al. (21) were among the first investigators to test this method. Subjects wore Canadian Forces chemical protective suits in an ambient temperature of 23°C, and walked for 40 min at moderate (4.5 $\text{km} \cdot \text{h}^{-1}$ and 5% slope) and low (4.0 $\text{km} \cdot \text{h}^{-1}$ and 0% slope) work rates. During the final 20 min of exercise, in active cooling trials, subjects immersed only their gloved hands in water ranging from 10 to 30°C. During moderate work, hand immersion attenuated the rise in core temperature with the effect being greater as water temperature decreased; this effect was not seen at lower work rates. Average hand heat loss for the two work rates were 112 W in 10°C water and 81 W in 20°C water. These heat loss values were higher than the rates seen in the present study. Although gloves were worn in the former study, hand immersion occurred during exercise, thus higher peripheral blood flow would be expected to conduct more heat to the calorimeter used in that protocol. Neither study demonstrated any evidence of significant vasoconstriction at lower water temperatures.

Allsopp and Poole (1) studied subjects who wore impermeable nuclear biological chemical protective suits while exercising in a warm environment of 30°C and 50% relative humidity. Subjects performed three exercise bouts, each followed by 20 min of rest. The three exercise bouts continued until T_{ac} reached 37.5, 38.0, and 38.5°C, respectively. The NBC suits were kept on during the rest periods, which included either control, or gloved hand only immersion in 10 or 25°C water. Hand immersion reduced core temperature, allowing subjects to perform more work between rest periods, with the effects being greater in the 10°C condition.

The present study demonstrated that hand immersion in 20°C did not decrease core temperature compared with Control conditions, while hand immersion in 10°C did. Cooling during both of the previous studies (1,21) occurred while subjects continued to wear vapor-impermeable protective clothing. Under these conditions a greater proportion of the total heat loss would occur through the immersed hands. Thus, effects of different water temperature on core cooling would be more evident than in the present study where passive cooling through the lightly clothed torso would comprise a significant portion of total heat loss.

Heavy firefighting clothing has been tested in subjects who performed a step test in 40°C air until their esophageal temperature reached 38.5°C (16). The firefighting gear remained on during a 30-min rest period in the 40°C air, which included either no cooling intervention or immersion of the naked hands in 10, 20, or 30°C water. In the first 20 min of cooling, hand immersion in 10°C and 20°C water decreased core temperature by 1.6 and 1.3°C, respectively; these decreases were about 40–60% more than seen in the present study. This greater core cooling may result from the higher cooling gradient as subjects in the study by House et al. (16) had a higher initial core temperature than those in the present study. It is noteworthy that when these resting subjects remained in a warm environment and continued to wear their firefighting gear, core temperature did not decrease. In the present study, subjects exited the heat and removed their heavy equipment and clothing before resting. Additional passive heat loss from the torso likely contributed to core cooling, even in Control conditions by up to 1.0°C in 20 min. In general, heat loss and cooling potential has predictably been greater in studies on firefighter clothing, when naked hands are immersed (16 and the present study) compared with studies on NBC suits, when hands must be gloved during immersion (1,21).

T_{ac} decreased during rest in all conditions including Control. Passive cooling occurred in each condition as heat production decreased with cessation of exercise and clothing and SCBA were removed. This insulation was removed in all conditions, including Control, in order to maintain a constant passive cooling component for every trial. As well, removal of this equipment would be a normal procedure in the field, especially in the absence of active cooling measures. Radiative and evaporative heat loss to the 21°C environment from non-actively cooled skin (i.e., the torso) was likely similar in all conditions as upper arm heat loss was not affected by forearm immersion (Fig. 2).

T_{ac} transiently continued to decrease following rest/cooling periods for 8–12 min, with the effect during HF-10 being double the values in all other conditions. This was expected as after-drop following cooling is a function of physical factors (i.e., the temperature gradients within tissue) and physiological factors (i.e., arterial blood cooling within cold tissue before returning to the heart) (12,13,14). The average tissue temperature of the forearm and hand would be lowest following immersion in 10°C (3), thus providing the greatest heat sink during subsequent exercise and the greatest after-drop.

Heat transfer between the water and body core is dependant on the water temperature, the core-to-surface temperature gradient, and importantly, blood flow in the distal limb, especially at/or near the skin surface. Vanggaard and Gjerloff (30) proposed that if arteriovenous anastomoses in the fingers and hands are open, venous return from the distal limb would flow primarily through surface veins in the forearms. Thus the forearms serve an important function as a heat exchanger which is dependant on peripheral vasodilation. The effectiveness of including the forearms in immersion for warming the core was demonstrated by Vanggaard et al. (29) in cold subjects. Once vasoconstriction was reversed during hand and forearm immersion in 45°C water, the core warmed at an impressive rate of almost $10°C \cdot h^{-1}$. Likewise, when trying to cool a heat-stressed subject, hand and forearm immersion in cool/cold water should also be effective in cooling the core as long as significant vasoconstriction does not occur. The elevated core temperature at the end of exercise promotes higher blood flow through the hands and forearms (26). Initially, this relatively higher blood flow should continue even though the forearms are cold.

In the present study the cooling rate was consistently attenuated after about 10 min of rest/cooling, a point at which core temperature had decreased to ~0.5–0.6°C above baseline values. Initially, peripheral blood flow will be enhanced at higher core temperatures (26). Continued decrease in core temperature would result in a gradual onset of peripheral vasoconstriction, which would confine more heat to the core (19,28) and attenuate core cooling. One other effect of lower core temperature would be the decreased core-to-water temperature gradient. Peripheral vasoconstriction is a graded phenomenon (5) which responds primarily to changes in the integrated thermal signal from skin and core thermoreceptors (2,6). Our results indicated that vasoconstriction was not complete in any condition as cooling continued throughout, ranging between 0.8 to $2.2°C \cdot h^{-1}$. It is important to note that the core cooling rate during the last 10 min of cooling was not any less during HF-10 than any of the other conditions; thus additional immersion of the forearms in 10°C water did not provide enough thermal stimulus to result in an exaggerated vasoconstriction. This is consistent with other studies where core cooling seemed to be unrestricted when naked or gloved hands were immersed in 10 or 0°C water, respectively (16,17). Based on past and present studies it seems that, when the hands and/or forearms were immersed in cold water following exercise in the heat, the integrated thermal signal was still high enough (due to elevated core temperature and high skin temperature on the non-actively cooled portions of the body) to maintain some level of peripheral blood flow (2,6).

Finally, active cooling of the hands and/or forearms decreased sweat loss by one-quarter to one-third of a liter compared with the Control condition. Average arm skin temperature during active cooling was consistently lower than Control; with values ranging from 7°C lower in H-20 to 16°C lower in HF-10 conditions. The decreased sweat rate during active cooling (which comprised 60 min of the 120-min protocol) is, therefore, consistent with the general dependence of sweat rate on skin temperature (25). As there were no differences in sweat rate between the active cooling conditions, it is not surprising that no significant correlations were found between sweat rate and changes in core and skin temperature, or total arm heat loss. Skin temperature or heat loss was not measured from the rest of the body. During active cooling conditions, however, it is possible that considerable passive torso cooling through wet clothing provided a proportionately large enough signal to inhibit sweating that differences in sweating between these conditions were attenuated.

Firefighters work in hot environments while wearing heavy clothing that is vapor impermeable. This type of ensemble restricts radiation, convective, and evaporative heat losses. This heat-dissipation problem is comparable to that posed by chemical/biological protective gear; however, the advantage of firefighter gear is that is can be taken off during rest periods and the naked hands and/or forearms can be immersed in cold water to maximize heat loss to the cold water. Water is readily available at firefighting scenes and it is generally cool enough to provide an effective heat sink. As long as there are containers large enough, both the hands and forearms can be easily immersed with no added equipment requirements. Although our data suggest a core cooling advantage to hand and forearm immersion, there was also considerable core cooling in Control conditions when only passive cooling occurred from the uninsulated arms and torso in a cooler environment. This procedure provided a clear advantage compared with resting in a warm environment while continuing to wear heavy clothing (16).

In conclusion, distal limb immersion in cool water is simple, practical, reduces heat strain, and may increase work performance in a hot, humid environment. With 20°C water, forearms should be immersed with the hands to be effective. At lower temperatures, forearm and/or hand immersion will be effective, although increasing surface area for heat transfer with forearm immersion will be advantageous. If forearm immersion is not practical, workers should at least exit the hot environment during rest periods and remove as much heavy clothing as practical in order to increase passive heat loss.

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