J Appl Physiol 94: 1317–1323, 2003.
First published November 27, 2002; 10.1152/japplphysiol.00541.2002.

Effect of water temperature on cooling efficiency during hyperthermia in humans

C. I. Proulx,[1] M. B. Ducharme,[1,2] and G. P. Kenny[1]
[1]*Faculty of Health Sciences, University of Ottawa, Ottawa K1N 6N5; and* [2]*Defence R&D Canada-Toronto, Toronto, Ontario, Canada M3M 3B9*

Submitted 21 June 2002; accepted in final form 4 November 2002

Proulx, C. I., M. B. Ducharme, and G. P. Kenny. Effect of water temperature on cooling efficiency during hyperthermia in humans. *J Appl Physiol* 94: 1317–1323, 2003. First published November 27, 2002; 10.1152/japplphysiol.00541.2002.—We evaluated the cooling rate of hyperthermic subjects, as measured by rectal temperature (T_{re}), during immersion in a range of water temperatures. On 4 separate days, seven subjects (4 men, 3 women) exercised at 65% maximal oxygen consumption at an ambient temperature of 39°C until T_{re} increased to 40°C (45.4 ± 4.1 min). After exercise, the subjects were immersed in a circulated water bath controlled at 2, 8, 14, or 20°C until T_{re} returned to 37.5°C. No difference in cooling rate was observed between the immersions at 8, 14, and 20°C despite the differences in the skin surface-to-water temperature gradient, possibly because of the presence of shivering at 8 and 14°C. Compared with the other conditions, however, the rate of cooling (0.35 ± 0.14°C/min) was significantly greater during the 2°C water immersion, in which shivering was seldom observed. This rate was almost twice as much as the other conditions ($P < 0.05$). Our results suggest that 2°C water is the most effective immersion treatment for exercise-induced hyperthermia.

water immersion; rectal temperature; core temperature; heatstroke; treatment

PARTICIPATION IN VARIOUS SPORTS, as well as military operations or industrial work, can put individuals at risk of suffering from heatstroke and other heat-related illnesses, especially when these activities are done in the heat. Heatstroke is a serious medical condition that requires immediate attention. The extent of tissue damage and physiological malfunctions depend not only on the degree of hyperthermia but also on the duration that the body remains at a high temperature (15, 20, 23). The main objective in the treatment of hyperthermia is therefore to reduce the body temperature to a safe level as quickly as possible.

A certain disagreement presently exists, however, over which treatment modality provides the fastest cooling (2, 10, 15). Some studies have provided support for the use of whole body water immersion for the treatment of hyperthermia (2, 4, 11), whereas others support enhancing evaporative cooling through various combination of water and air sprays as the most effective method of reducing high body temperature (29, 30). One of these studies (29), however, used tympanic temperature as an indication of core temperature. Given the knowledge that wind can influence the tympanic membrane temperature (13) and that the ear canal temperature can contaminate its measurement, the use of this site has to be questioned when it comes to evaluating the effectiveness of artificially enhanced evaporative cooling. Besides the present controversies over treatment modalities, disagreement also exists in regard to the specificity of the different cooling methods. Some of the highest cooling rates in the literature, notwithstanding the results from Weiner and Khogali (29), have been obtained with the use of water immersion (2, 4, 11). It has been advocated, however, that ice water immersion should not be used to cool hyperthermic patients because it induces vasoconstriction and shivering (1, 10, 25, 29). Yet ice water immersion has been successfully used to treat hyperthermic and heatstroked individuals (2, 4). Although Magazanik et al. (15) evaluated the relative effectiveness of varying water immersion temperatures to cool heatstroked dogs, to our knowledge, no study has systematically investigated in humans the cooling rate during immersion in a range of water temperatures. The objective of this study is therefore to evaluate the effectiveness of water temperatures ranging from 2 to 20°C for the whole body cooling of individuals rendered hyperthermic by exercise. It was hypothesized that the cooling rate would increase as the water immersion temperature decreased. Therefore, a hyperthermic individual's core temperature would be reduced faster in 2°C water compared with the other water immersion temperatures.

METHODS

Subjects. With approval from the Health Sciences and Science Research Ethics Board, seven healthy subjects (3 women, 4 men) gave informed consent to participate in this study. The subjects' characteristics are presented in Table 1. The seven subjects were 22 ± 1.9 yr old, had a mass of 68.4 ± 11.1 kg, and were 170.3 ± 7.3 cm tall (means ± SD). The subjects were physically active with a maximal oxygen consumption ($\dot{V}O_{2\,max}$) of 47.2 ± 5.2 and 60.0 ± 11.6 ml·kg^{-1}·

Address for reprint requests and other correspondence: G. P. Kenny, Univ. of Ottawa, School of Human Kinetics, Faculty of Health Sciences, Human Performance and Environmental Medicine Research Laboratory, Montpetit Hall, Rm. 376, 125 University Ave., Ottawa, Ontario, Canada K1N 6N5 (E-mail: gkenny@uottawa.ca).

Table 1. *Subjects' characteristics*

Subject	Sex	Age, yr	Height, cm	Weight, kg	Surface Area, m^2	Sum of 7 Skinfolds, mm	Body Fat, %	$\dot{V}O_{2\,max}$, ml·kg^{-1}·mm^{-1}
1	F	26	168.0	62.2	1.70	75.0	18.5	50.5
2	F	21	171.0	64.9	1.76	117.5	21.1	49.8
3	F	22	155.5	61.2	1.60	154.2	27.9	41.2
4	M	21	178.0	90.0	2.08	159.6	18.6	57.5
5	M	24	173.0	65.9	1.78	42.7	9.3	65.1
6	M	22	175.5	58.4	1.71	46.8	5.0	72.3
7	M	21	171.0	76.5	1.88	116.4	18.0	45.2
Average		22	170.3	68.4	1.79	101.7	16.9	54.5
SD		1.9	7.3	11.1	0.15	47.9	7.6	11.1

*Surface area = weight (kg)$^{0.425}$·height (cm)$^{0.725}$·0.007184 (7). Sum of 7 skinfolds and body fat determinations were made according to Jackson and Pollock (3) and Siri (24), respectively. $\dot{V}O_{2\,max}$, maximal oxygen consumption.

min^{-1} for women and men, respectively. Skinfolds were measured at the chest, axilla, triceps, subscapular, abdominal, suprailiac, and front thigh sites according to the Jackson and Pollock method (3). Percentage of body fat was estimated by hydrostatic weighing by use of the Siri equation (24). Women had an average of 22.5 ± 4.9% body fat, whereas men had 12.7 ± 6.7% body fat. Each subject participated in four experimental sessions.

Instrumentation. Rectal temperature (T_{re}) was measured by a rectal thermocouple inserted to a depth of 12 cm past the anal sphincter. Skin temperature was monitored at 12 sites by type T thermocouples integrated into heat flow sensors (Concept Engineering, Old Saybrook, CT). These were commercially available heat flow disks that can read both the heat loss and the skin temperature. The skin temperature is measured from the thermocouple that is integrated to the disk. The area-weighted mean skin temperature (T_{sk}) and mean heat loss (H_{sk}) were calculated by assigning the following regional percentages: head 6%, upper arm 9%, forearm 6%, finger 2%, chest 9.5%, abdomen 9.5%, upper back 9.5%, lower back 9.5%, anterior thigh 10%, posterior thigh 10%, anterior calf 9.5%, posterior calf 9.5% (8). T_{sk} (as well as H_{sk}) was thus calculated by using the equation $T_{sk} = (0.06 \times T_{forehead}) + (0.09 \times T_{upper\ arm}) + (0.06 \times T_{forearm}) + (0.02 \times T_{finger}) + (0.095 \times T_{chest}) + (0.095 \times T_{abdomen}) + (0.095 \times T_{upper\ back}) + (0.095 \times T_{lower\ back}) + (0.10 \times T_{anterior\ thigh}) + (0.10 \times T_{posterior\ thigh}) + (0.095 \times T_{anterior\ calf}) + (0.095 \times T_{posterior\ calf})$ where subscripts indicate the site of measurement. During the water immersion, the average skin temperature for the sites immersed in water ($T_{sk\text{-}im}$) was calculated by assigning the following regional percentages: upper back 12%, lower back 12.5%, abdomen 12.5%, upper arm 9.5%, forearm 9.5%, finger 2%, anterior thigh 12%, posterior thigh 12%, anterior calf 9%, posterior calf 9% (8, 12). Because the head and the chest were not entirely immersed in water for every subject, they were therefore not used to calculate $T_{sk\text{-}im}$. Heart rate was also monitored continuously (Polar Vantage). Temperatures were collected and digitized (Hewlett-Packard data-acquisition module, model 3497 A) at 5-s intervals, displayed graphically on the computer screen, and recorded in spreadsheet format on a hard disk (Hewlett-Packard, model PC-312, 9000).

Protocol. All four trials for each subject were conducted at the same time of day. Subjects were instructed to abstain from caffeine and alcohol as well as from any physical activity for a period of 12 h before each trial. Subjects were also instructed to refrain from eating and drinking (except water) for 2 h before the experiments and to consume 250 ml of water for every waking hour before the start of the experiments. The trials were separated by a minimum of 48 h. To control for hormonal effects, female subjects were tested during the follicular phase of their menstrual cycle.

On arrival at the laboratory, subjects were clothed in shorts (and a cotton/spandex bra top for women) and were instrumented appropriately. Baseline data were collected over 15 min while the subjects sat quietly at an ambient temperature of 25.7 ± 1.4°C. Subjects then entered the thermal chamber, where the ambient temperature was 38.8 ± 0.6°C and the relative humidity was 36.5 ± 0.1%. They exercised on a treadmill at 65% of their $\dot{V}O_{2\,max}$ until their T_{re} reached 40.0°C. The subjects' $\dot{V}O_{2\,max}$ was measured on a treadmill during the preliminary session by increasing the inclination of the treadmill by 2% every 2 min while maintaining the speed of the treadmill constant (5 mph for women and 6 mph for men). The workload that corresponded to 65% of the subjects' $\dot{V}O_{2\,max}$ was used during the trials. Two subjects were unable to reach the target temperature of 40.0°C because of physical exhaustion; therefore, for these two subjects, the exercise session for all trials was terminated when their T_{re} reached 39.5°C. The relative humidity inside the chamber had reached 58.6 ± 0.1% by the end of the exercise period. After the exercise period, subjects were immersed up to the clavicles in a circulated water bath at either 2, 8, 14, or 20°C, until their T_{re} returned to 37.5°C (one tall subject was only immersed to midchest level). The transition period from the end of the exercise to the start of the cooling period was an average 2.73 ± 0.98 min. This allowed for the subjects to exit the thermal chamber and, with the help of the experimenter, put on neoprene mitts and socks before entering the water bath. The mitts and socks were worn to minimize the risk of developing nonfreezing cold injuries at the extremities during exposure to the coldest water temperature, in addition to minimizing excessive discomfort. All throughout the immersion period, the water temperature was monitored with a thermocouple and adjusted when necessary by the addition of ice. The order of the trials was randomly assigned. Subjects then exited the water bath and sat quietly for a 30-min recovery period.

Data analysis. All the data were averaged for the baseline period (15 min). The following variables were calculated for each trial: exercise length, warming rate during the exercise period and cooling rate during the immersion period for T_{re}, area-weighted mean H_{sk}, T_{sk}, $T_{sk\text{-}im}$, and skin surface-to-water temperature gradient, lowest T_{re} attained after water immersion, afterdrop (difference between T_{re} on exit from cold water and its nadir) and the time to nadir, as well as heart rate. Data for the four trials were compared by using an ANOVA for repeated measures, and a Scheffé's post hoc test

Table 2. *Average rate of change of rectal temperature during the exercise period and end-exercise core temperatures*

	Water Temperature Conditions			
	2°C	8°C	14°C	20°C
Warming rate, °C/min	0.06 ± 0.02	0.05 ± 0.02	0.06 ± 0.02	0.07 ± 0.01
End-exercise temperature, °C	39.8 ± 0.3	39.8 ± 0.2	39.8 ± 0.3	39.8 ± 0.2

Values are means ± SD.

was used to identify significant differences. Results are reported as means ± SD (or as SE in the case of figures), and $P < 0.05$ identified statistically significant differences.

RESULTS

The seven subjects exercised on average for 45.4 ± 4.1 min. There was no significant difference between the four trial conditions in regard to the exercise length, the warming rate during exercise, or the end-exercise T_{re} (Table 2). This implies that the degree of hyperthermia was identical for all four conditions.

Cooling rate. The change in T_{re} during the four immersion temperatures is shown in Fig. 1. Core cooling rates were calculated as a function of the time required for T_{re} to return to 37.5°C. The core cooling rate during the 2°C water immersion was significantly greater than the core cooling rates for the 8, 14, and 20°C water immersion ($P = 0.001$; Table 3). There was no difference, however, in core cooling rates between the 8, 14, and 20°C immersion trials ($P = 0.360$). The cooling rate in regard to the first degree Celsius drop in core temperature (~40 to 39°C) was not significantly different for the 2°C water immersion compared with the other water immersion temperatures. However, during the second degree drop in core temperature (~39 to 38°C), the cooling rate associated with the 2°C water immersion was two times faster than the cooling

Table 3. *Cooling rates at different intervals of core temperature during whole body water immersion*

	Cooling Rates, °C/min		
	1st degree Celsius drop (~40 to 39°C)	2nd degree Celsius drop (~39 to 38°C)	Entire immersion period (until T_{re} = 37.5°C)
2°C	0.28 ± 0.14	0.50 ± 0.20†‡§	0.35 ± 0.14†‡§
8°C	0.17 ± 0.06	0.24 ± 0.11*	0.19 ± 0.07*
14°C	0.23 ± 0.09	0.19 ± 0.12*	0.15 ± 0.06*
20°C	0.26 ± 0.16	0.24 ± 0.12*	0.19 ± 0.10*

Values are means ± SD. The cooling rates are based on rectal temperature (T_{re}). *Significantly different from 2°C ($P < 0.05$); †significantly different from 8°C ($P < 0.05$); ‡significantly different from 14°C ($P < 0.05$); §significantly different from 20°C ($P < 0.05$).

rates associated with the immersions in 8, 14, and 20°C water (Table 3).

Figure 2 shows $T_{sk\text{-}im}$ during the water immersions. Throughout the 2°C water immersion, the $T_{sk\text{-}im}$ was significantly lower than during the 8, 14, and the 20°C water immersions. The minimal $T_{sk\text{-}im}$ values obtained were 10.5 ± 1.7, 12.6 ± 1.5, 17.4 ± 0.9, and 23.2 ± 1.1°C for the 2, 8, 14, and 20°C water immersions, respectively. Even though the minimal T_{sk} was obtained during the 2°C water immersion, a greater temperature gradient between the skin surface and the water was nonetheless present during this 2°C trial (7.7 ± 1.7°C) compared with the other water immersion temperatures (4.2 ± 1.5, 3.1 ± 0.9, and 3.0 ± 1.3°C for 8, 14, and 20°C water immersions, respectively). In fact, the temperature gradient at the end of the 2°C water immersion was 1.8, 2.5, and 2.6 times greater than during the 8, 14, and 20°C water immersions, respectively. On average, for the duration of the cooling period, the rate of heat loss was significantly greater during the 2°C water immersion compared with the other water immersion temperatures ($P < 0.001$; Table 4). No significant difference was found between the four water immersion temperatures in regard to the heat loss from the head and in regard to the change in

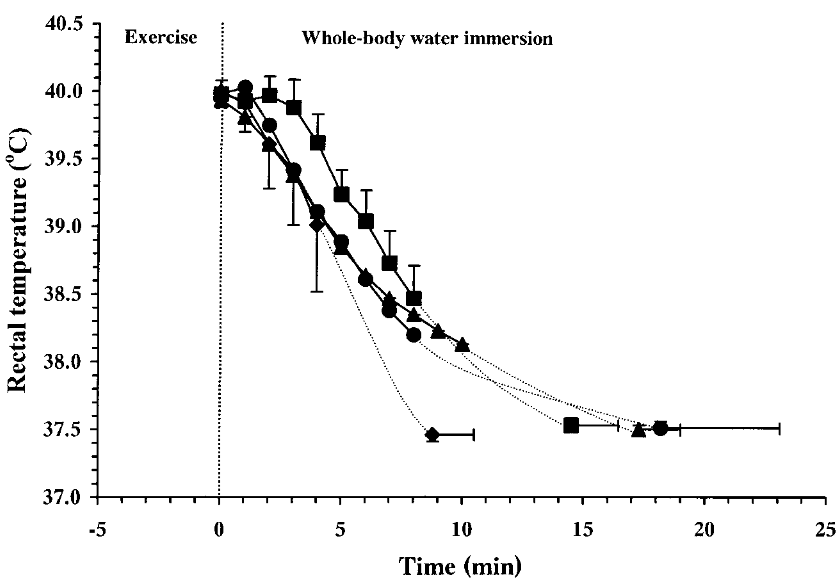

Fig. 1. Mean ± SE rectal temperature during immersion in 2°C (◆), 8°C (■), 14°C (▲), and 20°C (●) circulated water bath. Because the immersion times were different for each subject, the data are only represented until the longest immersion time common to all 7 subjects, i.e., the time just before the first subject exited the water bath (identified by the solid line). The average rectal temperature at the average immersion time for each condition is also identified and is joined by a dashed line. Subjects were removed from the water when their rectal temperature reached 37.5°C.

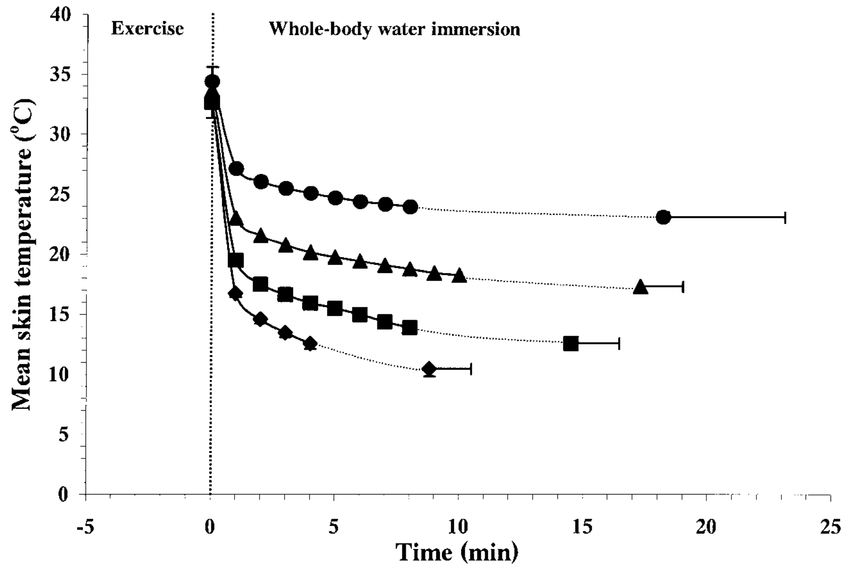

Fig. 2. Mean ± SE skin temperature during immersion in 2°C (◆), 8°C (■), 14°C (▲), and 20°C (●) circulated water bath. Because the immersion times were different for each subject, the data are only represented until the longest immersion time common to all 7 subjects (identified by the solid line). The average skin temperature at the average immersion time for each condition is also identified and is joined by a dashed line.

skin temperature of the forehead during the immersions. The average heat loss from the head for the four different water temperatures was 8.2 ± 1.9 kJ/m^2. The overall change in forehead temperature was of 3.6 ± 0.8°C to reach a minimal value of 33.8 ± 0.7°C by the end of the immersion period.

Heart rates during the water immersions were used as an indication of shivering. As the subjects recovered from the exercise session during the initial portion of the immersion, their heart rate slowed down progressively. A sudden sustained increase in heart rate was therefore associated with the start of shivering. It was assumed that the higher the heart rate, the higher the shivering intensity (27). It was also assumed that if the individual's heart rate failed to increase during the immersion, shivering was not present. These assumptions were corroborated by visual observations. As can be seen by the heart rate values from Fig. 3, which are substantiated by the visual observations from Table 5, shivering was seldom seen during the 2 and 20°C water immersions. During the 8°C water immersion, however, subjects began shivering around the 9th minute, whereas they started shivering around the 11–12th minute during the 14°C water immersion.

After subjects exited the water bath, their T_{re} continued to drop for all four water immersion temperatures. The postcooling afterdrop, however, was significantly greater for the 2°C water immersion compared with the 14 and 20°C water immersions (P = 0.003; Table 6). As well, the nadir was significantly lower after the 2°C water immersion (T_{re} = 35.70°C) compared with the 14 and 20°C water immersions (P = 0.003). There was no difference, though, between conditions in regard to the time required for T_{re} to reach its nadir.

DISCUSSION

The cooling rate was about two times greater during the 2°C water immersion compared with the 8, 14, and 20°C water immersions. During the 2°C water immersion, $T_{sk\text{-}im}$ was significantly lower, thus creating a greater temperature gradient between the core and the periphery. Furthermore, the temperature gradient between the skin surface and the water was also significantly higher during the 2°C water immersion. This greater thermal gradient between the core and the periphery as well as between the periphery (skin surface) and the surrounding water allows the heat to be dissipated at a faster rate during the 2°C water immersion compared with the other water immersion temperatures.

Yet the temperature gradient is not the only factor to consider when cooling hyperthermic individuals. Because heat storage is dependent on both endogenous heat production and heat exchanges with the environ-

Table 4. *Overall rate of heat loss during whole body water immersion*

	Water Temperature Conditions			
	2°C	8°C	14°C	20°C
Rate of heat loss				
W/m^2	1,304.5 ± 257.8†‡§	941.7 ± 190.4*§	736.7 ± 129.9*	631.3 ± 137.2*†
kJ/min	115.76 ± 12.94†‡§	78.16 ± 13.21*§	63.22 ± 13.77*	55.56 ± 12.95*†
$kJ \cdot min^{-1} \cdot kg^{-1}$	1.73 ± 0.32†‡§	1.16 ± 0.25*§	0.93 ± 0.23*	0.82 ± 0.18*†

Values are means ± SD. *Significantly different from 2°C ($P < 0.05$); †significantly different from 8°C ($P < 0.05$); ‡significantly different from 14°C ($P < 0.05$); §significantly different from 20°C ($P < 0.05$).

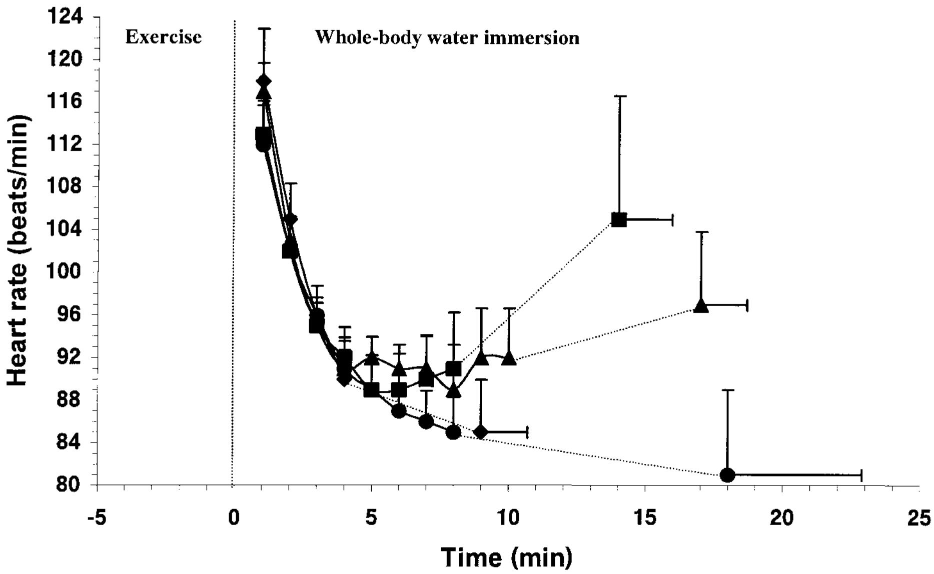

Fig. 3. Mean ± SE heart rate values during immersion in 2°C (◆), 8°C (■), 14°C (▲), and 20°C (●) circulated water bath. The heart rate values were first noted 1 min after the start of immersion to minimize the effect of the transition from the chamber to the water bath. Because the immersion times were different for each subject, the data are only represented until the longest immersion time that was common to all 7 subjects, i.e., the time just before the first subject exited the water bath (identified by the solid line). The average heart rates of the subjects remaining in the water at the average immersion time for each condition are also identified and are joined by a dashed line.

ment, any increase in metabolic heat production, such as with shivering, can substantially reduce the rate at which core temperature drops. Shivering, however, was seldom observed during the 2°C water immersion.

Table 5. *Visual observations of shivering*

Immersion Time, min	Water Temperature Conditions 2°C	8°C	14°C	20°C
1	no shivering	no shivering	no shivering	no shivering
2	**[7]**	**[7]**	**[7]**	**[7]**
3				
4				
5	**[6]**			
6	**[4]**	shivering (1)		
7	**[3]**	shivering (3)	shivering (1)	
8	shivering (1)	shivering (3)	shivering (1)	
9		shivering (6) **[6]**	shivering (2)	**[5]**
10			shivering (3)	
11			shivering (3) **[6]**	
12		**[4]**	shivering (4)	shivering (1)
13	**[2]**			shivering (1) **[4]**
14	**[1]**	**[3]**	**[5]**	shivering (2)
15			**[4]**	**[3]**
16	**[0]**			
17		**[2]**		
18				
19		**[1]**		**[2]**
20			**[2]**	
21				**[1]**
22			**[1]**	
23			**[0]**	
24		**[0]**		**[1]**

Numbers in parenthesis indicate the total number of subjects that were shivering. Bold numbers in brackets indicate how many subjects were still in the water at the different time points.

The present study is not the only one to have observed a lack of shivering during 2°C water immersion. Indeed, Armstrong et al. (2) also noted this absence of shivering during ice water immersion of heatstroked victims. The absence of shivering in the present study could be attributed to the short duration of the water immersion. In fact, although the average length of the immersion in the 2°C water was 8.8 min, some subjects stayed in the water for only 4 or 5 min, which corresponded to the time necessary for their T_{re} to return to 37.5°C. Likewise, almost no shivering was present during the 20°C water immersion. Therefore, even though the temperature gradients between the core and the periphery as well as between the periphery (skin) and the surrounding water were lower during the 20°C water immersion, the cooling rate was nonetheless similar to the 8 and 14°C water immersions. According to the subjects' heart rates during the immersions, the shivering intensity was higher during the 8°C water immersion compared with the 14°C water immersion. Furthermore, the subjects started shivering earlier during the 8°C water immersion (9th minute) compared with the 14°C water immersion (11–12th minute). Likewise, Wyndham et al. (30) reported that their subjects shivered either continuously or intermittently after 10 min of immersion in 14.4°C water. On the other hand, Weiner and Khogali's (29) subjects were shivering continuously after only 6 min of immersion in 15°C water. The degree of hyperthermia in Weiner and Khogali's study, however, wasn't as high as in either the present or Wyndham et al.'s study, in which the subjects reached a T_{re} of 40.0°C before being cooled. The subjects in Weiner and Khogali's study only reached a tympanic temperature of 39.5°C, which may explain why they started shivering earlier.

The results of this study disprove the notion that heat loss is impeded during immersion in ice water as a result of intense vasoconstriction and shivering. On the basis of the heat loss data, it is evident that im-

Table 6. *Afterdrop after whole body water immersion*

	2°C	8°C	14°C	20°C
Nadir, °C	35.70 ± 0.74†‡	36.03 ± 0.65	36.28 ± 0.81*	36.34 ± 0.50*
Afterdrop, °C	1.76 ± 0.75†‡	1.51 ± 0.65	1.23 ± 0.79*	1.17 ± 0.48*
Time to nadir, min	20.7 ± 7.7	24.0 ± 5.7	22.3 ± 10.3	23.5 ± 5.3

Values are means ± SD. Afterdrop, difference between core temperature on exit from water and its nadir; time to nadir, time for the core temperature to reach its nadir. *Significantly different from 2°C ($P < 0.05$); †significantly different from 14°C ($P < 0.05$); ‡significantly different from 20°C ($P < 0.05$).

mersion in 2°C water provided the greatest rate of heat loss. Noakes (18) states that the vasoconstriction of skin blood vessels is not an efficient way to protect core temperature during immersion in cold water. In fact, skeletal muscles seem to play the major role when it comes to isolating the body during cold water immersion (5). Because the temperature gradient between the skin and the ice water is so great, an abundant skin blood flow is not essential for the body to cool (2). Furthermore, even though the peripheral blood flow is controlled by both central and cutaneous receptors, central receptors seem to be dominant. Thus, when the core temperature is elevated, as in the case of hyperthermia, the peripheral vasoconstriction would not be as intense as would have been anticipated under normal circumstances (28). This phenomenon can be attributed to the inhibition of the vasoconstriction response by the central receptors. In normothermic conditions (i.e., body temperature around 37.0°C), the central receptors would not override the cutaneous receptors. The peripheral vasoconstriction resulting from cold water immersion would therefore significantly reduce the rate of heat loss. In fact, McDonald et al. (16) obtained a cooling rate of only 0.019 ± 0.005°C/min when normothermic individuals (T_{re} = 37.1°C) were immersed in 19°C water for 60 min (T_{re} = 36.3°C) (16). Likewise, a cooling rate of 0.014 ± 0.010°C/min was obtained when normothermic subjects were immersed in 22°C water for 1 h or until their T_{re} dropped by 1°C (21). These cooling rates were significantly slower than the rate of 0.19 ± 0.10°C/min obtained in the present study with hyperthermic subjects immersed in 20°C water. We obtained a cooling rate of 0.15 ± 0.06°C/min in 14°C water immersion, whereas the first 40 min of immersion in 16°C water produced a cooling rate of only 0.028 ± 0.019°C/min in normothermic individuals (T_{re} = 37.2 ± 0.2°C) (17). The rate of cooling is thus dependent on the initial core temperature, the initial rate of cooling being higher in the presence of a high initial body temperature (19).

According to Tek and Olshaker (26), for a hyperthermia treatment to be considered effective, it must produce cooling rates in excess of 0.1–0.2°C/min. The cooling rate obtained in the present study during the 2°C water immersion (0.35°C/min) easily meets this criterion. This cooling rate is, however, superior to that obtained by Armstrong et al. (2) (0.20°C/min) and by Costrini (4) (0.15°C/min) during ice water immersion (1–3°C). These slower cooling rates can be partially attributed to the fact that these studies were accomplished in the field and implicated heatstroked victims. Furthermore, during Armstrong's study, the patients only had their torso and upper thighs in the water, which limits the potential for heat loss. To our knowledge, no other studies done in a laboratory have used immersion in ice water as a cooling strategy for hyperthermic individuals. Wyndham et al. (30) did use immersion in cold water (14.4°C) to cool participants whose T_{re} was at 40.0°C. Their cooling rate of 0.04°C/min is distinctively slower than the cooling rate obtained in the present study (0.15°C/min). This difference in cooling rate can be explained by the fact that, contrary to the present study, Wyndham' subjects were immersed in a noncirculated water bath. Because convection influences the rate at which an individual can cool by dispersing the boundary layer of water adjacent to the skin and thereby maintaining the thermal gradient essential to heat dissipation (9), their slower cooling rate can be expected. Kielblock (11) obtained a cooling rate of 0.26°C/min during immersion of hyperthermic subjects (2°C above baseline) in 12°C water. This cooling rate was somewhat faster than the cooling rates obtained in the present study during the 8 and 14°C water immersion (0.19 and 0.15°C/min, respectively). Certain studies carried out in laboratories indicated that cooling strategies that were based on evaporation were more effective than water immersion to cool hyperthermic individuals (29, 30). These studies, however, used cold water immersion (~15°C) instead of ice water immersion.

One concern related to water immersion is the risk of a core temperature afterdrop after exiting the water. After immersion in all four water immersion temperatures, T_{core} indeed continued to drop. After the 2°C water immersion, the afterdrop in regard to T_{re} (1.76°C) was significantly greater than for the water immersions at 14 and 20°C (P = 0.003). The T_{re} decreased to a nadir of 35.70°C. Considering that normothermia corresponds to a T_{core} between 36.8 and 37.7°C (14), this temperature represents a state of mild hypothermia. A similar afterdrop was reported after the 14°C water immersion of hyperthermic volunteers (T_{re} = 40.0°C). Their T_{re} fell by 0.56 to 1.67°C after they had exited from the water bath (30). This is comparable to the afterdrop of 1.23 ± 0.79°C encountered in the present study after the 14°C water immersion. Reduction of a few degrees in core temperature can create extreme discomfort and light-headedness. Further declines, which can be possibly brought on by the return of cold blood to the core after the exit from the water, can result in impairment of cardiovascular functions. Because the sinoatrial node is affected by hypothermia, a drop in cardiac rhythm, which leads to a drop in cardiac output, can result as the myocardium cools. The risk of ventricular fibrillation, as well as myocardium infarctions, increases as the heart's temperature drops further. Furthermore, the hypothalamus will also lose the ability to regulate body temperature if the core temperature drops too low. Because there are dangers inherent in the continued fall in core temperature after cold or ice water immersion, the degree of afterdrop is an important concern when individuals are recovering after water immersion. One fatality reported by Ferris et al. (6) could have been caused by excessive cooling. The patient's core temperature fell to 37.2°C during immersion in ice water and subsequently fell to 35.6°C after removal from the tub. This patient developed circulatory collapse, and although his core temperature was eventually raised, he subsequently died (6). Subjects suffered no ill effects from their participation in the present study. In fact, the 2°C water immersion did not elicit a greater degree of discomfort in the subjects compared with the other water immersion temperatures. It is nonetheless recommended to stop the treatment and to remove victims from the water when their T_{re} reaches ~38.0–38.5°C to avoid undershooting normal temperature and provoking a hypothermic state (9, 22, 23). Cooling patients in ice water to a core temperature of only 38.0–38.5°C will still provide a faster cooling rate compared with warmer temperatures.

In conclusion, immersion in 2°C water provided the fastest rate of core cooling and was therefore the most effective treatment in eliminating exercise-induced hyperthermia in young, healthy active subjects. No differences in core cooling rate were found, however, between immersions in 8, 14, or 20°C water.

The authors thank Julien Périard for assistance in the data collection.

This research was supported by the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

1. **Al-Aska AK, Yaqub BA, Al-Harthi SS, and Al-Dalaan A.** Rapid cooling in management of heat stroke: clinical methods and practical implications. *Annu Saudi Med* 7: 135–138, 1987.
2. **Armstrong LE, Crago AE, Adams R, Roberts WO, and Maresh CM.** Whole body cooling of hyperthermic runners: comparison of two field therapies. *Am J Emerg Med* 14: 355–358, 1996.
3. **Canadian Society for Exercise Physiology.** *Certified Fitness Appraiser Resource Manual*. Gloucester, Ontario: CSEP, 1986.
4. **Costrini A.** Emergency treatment of exertional heatstroke and comparison of whole body cooling techniques. *Med Sci Sports Exerc* 22: 15–18, 1990.
5. **Ducharme MB and Tikuisis P.** In vivo thermal conductivity of the human forearm tissues. *J Appl Physiol* 70: 2682–2690, 1991.
6. **Ferris EB, Blankenhorn MA, Robinson HW, and Cullen GE.** Heat stroke: clinical and chemical observations on 44 cases. *J Clin Invest* 17: 249–262, 1938.
7. **Goheen MS, Ducharme MB, Kenny GP, Johnston CE, Frim J, Bristow GK, and Giesbrecht GG.** Efficacy of forced-air and inhalation rewarming by using a human model for severe hypothermia. *J Appl Physiol* 83: 1635–1640, 1997.
8. **Hardy JD and Dubois EF.** The technique of measuring radiation and convection. *J Nutr* 15: 461–475, 1938.
9. **Harker J and Gibson P.** Heat stroke: a review of rapid cooling techniques. *Intensive Crit Care Nurs* 11: 198–202, 1995.
10. **Khogali M.** The Makkah body cooling unit. In: *Heatstroke and Temperature Regulation*, edited by Khogali M and Hales JRS. Sydney, Australia: Academic, 1983, p. 139–148.
11. **Kielblock AJ.** Strategies for the prevention of heat disorders with particular reference to body cooling procedures. In: *Heat Stress: Physiological Exertion and Environment*, edited by Hales JRS and Richards DAB. Amsterdam, The Netherlands: Excerpta Medica, 1987, p. 489–497.
12. **Layton RP, Mints WH, Annis JF, Rack MJ, and Webb P.** Calorimetry with heat flux transducers: comparison with a suit calorimeter. *J Appl Physiol* 54: 1361–1367, 1983.
13. **Livingstone SD, Grayson J, Firm J, Allen CL, and Limmer RE.** Effect of cold exposure on various sites of core temperature measurements. *J Appl Physiol* 54: 1025–1031, 1983.
14. **Mackowiak PA, Wasserman SS, and Levine MM.** A critical appraisal of 98.6°F, the upper limit of the normal body temperature and other legacies of Carl Reinhold August Wunderlich. *JAMA* 268: 1578–1580, 1992.
15. **Magazanik A, Epstein Y, Udassin R, Shapiro Y, and Sohar E.** Tap water, an efficient method for cooling heatstroke victims — a model in dogs. *Aviat Space Environ Med* 9: 864–866, 1980.
16. **McDonald A, Goode RC, Livingstone SD, and Duffin J.** Body cooling in human males by cold-water immersion after vigorous exercise. *Undersea Biomed Res* 11: 81–90, 1984.
17. **Mittleman KD and Mekjavic IB.** Effect of occluded venous return on core temperature during cold water immersion. *J Appl Physiol* 65: 2709–2713, 1988.
18. **Noakes TD.** Body cooling as a method for reducing hyperthermia. *S Afr Med J* 69: 373–374, 1986.
19. **Richards R and Richards D.** Exertion-induced heat exhaustion and other medical aspects of the City-to-Surf fun runs. *Med J Aust* 141: 799–805, 1984.
20. **Richards R, Richards D, Schofield PJ, and Sutton JR.** Management of heat exhaustion in Sydney's The City-to-Surf fun runners. *Med J Aust* 2: 457–461, 1979.
21. **Romet TT and Hoskins RW.** Temperature and metabolic responses to inhalation and bath rewarming protocols. *Aviat Space Environ Med* 59: 630–634, 1988.
22. **Sandor RP.** Heat illness: on-site diagnosis and cooling. *Physician Sportsmed* 25: 35–40, 1997.
23. **Shapiro Y and Seidman DS.** Field and clinical observations of exertional heat stroke patients. *Med Sci Sports Exerc* 22: 6–14, 1990.
24. **Siri WE.** Gross composition of the body. In: *Advances in Biological and Medical Physics*, edited by Lawrence JH and Tobias CA. New York: Academic, 1956.
25. **Strydom NB, Kielblock AJ, and Schutte PC.** Heatstroke — its definition, diagnosis and treatment. *S Afr Med J* 61: 537, 1982.
26. **Tek D and Olshaker JS.** Heat illness. *Emerg Med Clin North Am* 10: 299–310, 1992.
27. **Tikuisis P, Ducharme MB, Moroz D, and Jacobs I.** Physiological responses of exercised-fatigued individuals exposed to wet-cold conditions. *J Appl Physiol* 86: 1319–1328, 1999.
28. **Tipton MJ, Allsopp AJ, Balmi PJ, and House JR.** Hand immersion as a method of cooling and rewarming. *J R Nav Med Serv* 79: 125–131, 1993.
29. **Weiner JS and Khogali M.** A physiological body-cooling unit for treatment of heat stroke. *Lancet* 1: 507–509, 1980.
30. **Wyndham CH, Strydom NB, and Cooke HM.** Methods of cooling subjects with hyperplexia. *J Appl Physiol* 14: 771–776, 1959.