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ORIGINAL ARTICLE

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Thermal regulatory responses to submaximal cycling following lower-body cooling in humans

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Abstract This study compared the effects of pre-exercise cooling with control water immersions on exercise-induced thermal loads derived from steady-state submaximal exercise. Eight healthy male participants [mean (SEM) age 29 (1) years, maximal oxygen uptake 3.81 (0.74) l·min^{-1}, and body surface area 1.85 (0.11) m^2] took part in experiments that included 30 min of baseline data collection [ambient temperature 21.3 (0.2°C)], 30 min of immersion in water to the level of the supra-iliac crest [water temperatures of 35.1 (0.3)°C for thermoneutral and 17.7 (0.5)°C for precooled treatments], and 60 min of cycling exercise at 60% of maximal oxygen uptake. No significant differences were noted during exercise in net mechanical efficiency, metabolic rate, O_2 pulse, or ratings of perceived exertion between the two treatments. Precooling resulted in a significant negative body heat storage during immersion and allowed greater heat storage during exercise. However, net body heat storage for the entire protocol was no different between treatments. Cooling significantly lowered rectal, mean skin, and mean body temperatures as well as more than doubling the exercise time until a 0.5°C rectal temperature increase was observed. The cooling trial significantly delayed onset of sweating by 19.62 min and decreased sweat rate by 255 ml·h^{-1} compared to control. Thermal and sweat sensation scores were lower after the cooling treatment compared to control. These data suggest that lower-body precooling is effective at decreasing body heat storage prior to exercise and decreases reliance on heat dissipation mechanisms during exercise. Therefore, this unique, well-tolerated cooling treatment should have a broader application than other precooling treatments.

Keywords Body heat storage · Metabolic heat production · Sweating · Thermal comfort · Water immersion

Introduction

Heat production associated with exercise poses a formidable challenge to temperature homeostasis. High internal temperature and body heat storage (*S*) are associated with the termination of work in animals (Fuller et al. 1998), healthy humans (Gonzalez-Alonso et al. 1999; MacDougall et al. 1974), and certain populations of patients (Petajan and White 1999). Exercise accompanied by either body cooling (Holmer 1989; Webb and Annis 1968) or in a cooler ambient temperature (Galloway and Maughan 1997), reduces the cardiovascular and thermal strain associated with exercise. Precooling is a behavioral strategy used to create negative heat storage prior to the initiation of exercise or thermal stress. This strategy has been used with varying results. Some investigators have reported clear thermal regulatory, circulatory or performance benefits (Booth et al. 1997; Hessemer et al. 1984; Lee and Haymes 1995; Olschewski and Bruck 1988; White et al. 2000) whilst others could show no real effect (Bolster et al. 1999; Drust et al. 2000; Marsh and Sleivert 1999) or even

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performance decrements (Bergh and Ekblom 1979; Kruk et al. 1990). These differences in results have probably been due to the varying methods and degrees of cooling; varying exercise durations, intensities, and modalities; and differing experimental ambient conditions, including temperature and humidity.

Potential ergogenic effects of precooling on exercise performance and temperature regulation have been briefly addressed in previous reviews (Horvath 1981; Petajan and White 1999). Theoretically, precooling should enable longer exercise durations, via a greater ability to increase S prior to reaching an upper critical temperature or overtly taxing heat dissipation mechanisms. Hence, by not reaching an upper critical temperature as rapidly, maximal work output should increase. Furthermore, by not activating autonomic heat dissipation mechanisms as early during exercise, fluid balance should be maintained longer, thermal effects on the cardiovascular system should be less, and thermal comfort should be greater.

Finding a practical yet effective precooling technique is difficult, however, but is important for both athletes and populations in which function is limited by the accumulation of S, such as in patients suffering from multiple sclerosis. Immersion in water is a viable method as it is easily carried out, has high heat transfer characteristics, and has been demonstrated to improve function in both maximal (Booth et al. 1997) and submaximal (White et al. 2000) exercise. The main difference between the precooling techniques used by the above two research studies was in the depth of water immersion. Head-out, whole-body water immersion was used by Booth et al. (1997), and lower-body water immersion to the supra-iliac crest was used by White et al. (2000). Lower-body water immersion was selected for the latter study because similar internal temperatures are observed in lower-body and in head-out water immersion (Lee et al. 1997), there is a lower metabolic response during precooling by lower-body compared to whole-body immersion in water (unpublished observations), and the combined finding that lower-body but not torso only water immersion is a beneficial precooling treatment (Marsh and Sleivert 1999; White et al. 2000). However, in our previous study (White et al. 2000), we did not address the mechanisms and time course of the precooling response, thermal comfort, or thermoregulatory effector responses.

There is limited research investigating the effects of the pre-exercise cooling of specific body segments, and published research has not addressed key issues such as the duration of the effect and thermoregulatory effector responses [e.g. skin temperature (T_{sk}), and sweat rate]. In addition, most literature on precooling describes the effect on maximal exercise, not steady-state intensities which lend themselves to better thermoregulatory comparisons. To the authors' knowledge, no studies have examined the effect of precooling the lower-body by immersion in water in terms of the accumulation of heat and its dissipation, the time course of the effect, and the efficacy of the treatment. To examine these questions, steady-state submaximal exercise at equal relative intensities was chosen to provide a consistent thermal load and to allow better intersubject comparisons. This study was designed to determine the physiological and perceptual effects of precooling the lower-body in water on the thermal loads induced by moderate exercise in normal ambient conditions.

Methods

Subjects

Eight healthy men [mean (SEM)] [body surface area (A_D) 1.85 (0.11) m^2, A_D to mass ratio 267 (3) cm^2·kg^{-1}, age 29 (1) years] participated in this study. Subjects were interviewed and determined not to be overtly acclimatized to cold or heat prior to participating in the study. Data were collected in the winter and early spring in a dry temperate climate and at an altitude of about 1,300 m. The protocol and the form for informed consent received institutional approval. Written informed consent was obtained from all participants prior to enrolling in this study.

Measurements

Mass

Body mass was assessed using a high resolution platform scale (General Electrics) connected to a digital readout (Rice Lake Weighing System) reading to the nearest 0.01 kg.

Temperature

The T_{sk} (°C) was measured by attaching banjo type surface temperature probes (Yellow Springs Instruments) to the calf, thigh, chest, and arm. Rectal temperatures (T_{re},°C) were measured using general use thermistors (Yellow Springs Instruments) inserted 10 cm past the anal sphincter. All temperature probes were connected to a digital thermistor readout unit (Digitec).

Metabolic and cardiovascular measurements

Heart rate was continuously monitored using a heart rate monitor (Polar). Metabolic rate and other ventilatory parameters were collected and analyzed using an automated metabolic cart (ParvoMedics).

Sweat

Whole-body sweat rate was determined from pre-post differences in body mass, the difference between the two measurements being the water loss of the skin and respiratory tract. Onset of sweating was determined using an automated dew point system (Graichen et al. 1982). Dew-point sensors were attached to the back, upper arm, and upper leg.

Participant perceptions

The 6–20 point Borg scale of perceived exertion (RPE) was used to determine the participants' perception of exercise intensity during exercise. A 9-point thermal sensation (0 = very cold to 8 = very hot), 5-point thermal discomfort (1 = comfortable to 5 = intolerable), and 5-point sweating sensation scales (1 = not at all to 5 = maximally) were used to determine the participants' thermal comfort during the protocol (DuBois et al. 1990).

Calculations

Temperature calculations

Four T_{sk} (°C) sites were used and weighted to give mean T_{sk} according to the following equation: mean $T_{sk} = 0.3(T_{sk,chest} + T_{sk,arm}) + 0.2(T_{sk,thigh} + T_{sk,calf})$ (Ramanathan 1964). Mean body temperature (T_b,°C) was assessed using the following weighting equation: mean $T_b = (0.65 \cdot T_c) + (0.35 \cdot \text{mean } T_{sk})$, where T_c (core temperature, °C) was indexed by T_{re} (Burton 1935).

Body heat storage

The S was estimated using the following equation: $S = 0.97 \cdot \text{mass} \cdot (\Delta \text{ mean } T_b \cdot \Delta t^{-1}) \cdot A_D{}^{-1}$, where Δ mean T_b is the change in mean body temperature and Δt (min) is the change in time (Holmer 1989).

Dry heat transfer

Radiant heat flux(R) was calculated using the equation: $R = 4.88 \cdot 10^{-8} \cdot (\text{mean } T_{sk}{}^4 - T_{rad}{}^4) \cdot A_r \cdot A_D{}^{-1}$, where $4.88 \cdot 10^{-8}$ is the Stefan-Boltzmann constant, T_{rad} (°C) is the radiant temperature of the environment, A_r (m^2)is the surface area of the body which is able to transfer heat by radiation (Mitchell et al. 1969). Convective heat flux (C) was calculated using the equation: $C = 6.23(P_b/760)^{0.6} \cdot v^{0.6} \cdot (\text{mean } T_{sk} - T_a) \cdot A_c \cdot A_D{}^{-1}$, where 6.23 is the forced convection coefficient, P_b is the ambient barometric pressure (mmHg) and 760 (mmHg) is sea level pressure, v (m·s^{-1}) is the wind velocity, A_c (m^2)is the surface area of the body able to transfer heat via convection (Mitchell et al. 1969).

Exercise efficiency

Net mechanical efficiency, as a percentage, was calculated according to the equation: net mechanical efficiency = (exercise intensity·100)·(metabolic rate–resting metabolic rate)$^{-1}$.

Protocol

On the initial visit, the subjects were interviewed and familiarized with the study procedures. They then performed a graded exercise test to determine maximal exercise intensities and metabolic and cardiovascular responses. The maximal exercise test was performed on a friction-braked cycle ergometer (Body Guard) with an initial intensity of 50 W for 2 min and increasing 50 W every 2 min until the subjects became fatigued. Maximal oxygen uptake was used to determine the exercise intensity for the submaximal exercise. The subjects returned to the laboratory on two more occasions separated by no longer than 10 days. They were tested at the same time of day and were instructed to keep similar sleep-wake cycles for the duration of the study. They were also instructed to drink 1 l of fluid every 4 waking-h and to eat similar meals in terms of their macronutrient compositions and timings during the 24 h prior to the tests. The subjects were in a postabsortive state for a minimum of 4 h prior to the tests. Finally, the subjects were instructed not to consume any caffeinated beverages on the day of the test and not to participate in any strenuous or unusual activity for the previous 24 h. These precautions were undertaken to minimize factors that could have affected the thermal regulatory responses.

After the subjects had been appropriately instrumented, measurements of body mass, temperature, and metabolic rate were made. Temperature and metabolic measurements were recorded during a 30 min baseline phase in which participants were seated at [mean (SEM)] T_a [i.e. 21.3 (0.2)°C and 22.4 (1.9)% relative humidity] and attired in socks and shorts. A brief transition period preceded immersion. The experiment was conducted using a cross-over design, with the first treatment (i.e. the cooling or the control immersion in water) being determined randomly. The alternate treatment was used on the next visit. Cooling treatment consisted of a 30 min immersion of the lower-body in water at 17.7 (0.5)°C. The control treatment consisted of a 30 min immersion of the lower-body in water at 35.1 (0.3)°C. Lower-body immersion consisted of the participant sitting on a nylon chair in a large metal tank filled to the level of the supra-iliac crest. The temperature of the precooling water has been previously shown to create a heat debt (White et al. 2000), whereas the temperature of the water during the control immersion has been demonstrated to be thermally neutral (Sagawa et al. 1988). Metabolic rate was measured during immersion to determine if thermoregulatory heat production had occurred. A transition phase, during which participants exited the immersion tank, removed excess water, changed into dry clothing (i.e. gym shorts, socks and gym shoes) and had lower-limb T_{sk} probes and automated dew point sensors attached, lasted approximately 15 min. The endogenous heat load consisted of cycling for 60 min (using the same ergometer as in the maximal exercise test) at an intensity that approximated 60% of maximal oxygen uptake. On the subsequent visit (separated by a minimum of 72 h), the subjects repeated this protocol, but at a different temperature of water immersion.

Data analysis

Means (SEM) are reported for dependent variables. Using commercially available software (SigmaStat), two-way repeated measurements ANOVA were used to determine whether there were significant differences for treatment and time. If significant main effects were observed, Student-Newman-Keuls post hoc analyses were performed to determine where differences existed between groups. Statistical significance was accepted at $P < 0.05$.

Results

Temperature responses

The T_{re} decreased ($P < 0.001$) slightly during both the control and cooling water immersions (see Table 1). The T_{re} after water immersion, prior to exercise, was 36.81 (0.09) after the control and 36.14 (0.18)°C after the cooling treatment. With the cooling treatment, the lowest T_{re} were not manifested until min 6–8 of exercise, which corresponded to a mean drop of 1°C from baseline values. The T_{re}, mean T_{sk}, and mean T_b significantly increased ($P < 0.001$) with increasing exercise duration. The cooling treatment resulted in significantly lower T_{re} throughout the 60 min of exercise, and maintained lower mean T_{sk} and mean T_b temperatures until min 24 and 34, respectively (see Fig. 1). The exercise duration until a 0.5°C increase above baseline in internal temperature had occurred was significantly ($P < 0.001$) prolonged after the cooling [33(2) min] compared to the control [15 (1) min] treatment.

Metabolic and cardiovascular responses

No differences ($P > 0.35$) were noted in mean net mechanical efficiency during exercise after the cooling [20.8 (0.5)%] or control [20.1 (0.6)%] treatments.

Table 1. Effect of water immersion condition on mean (SEM) rectal temperature (T_{re}), oxygen uptake ($\dot{V}O_2$), thermal sensation, and thermal discomfort; during baseline and 30 min of water immersion. *au* arbitrary units. Significance was accepted at the $P<0.05$ level

Variable	Condition	Base	Water immersion		
			10 min	20 min	30 min
T_{re} (°C)	Control	36.79 (0.09)	36.70 (0.09)[a]	36.64 (0.08)[a]	36.65 (0.09)[a]
	Cooling	36.83 (0.08)	36.76 (0.09)[a]	36.70 (0.08)[a,b]	36.60 (0.08)[a,b]
$\dot{V}O_2$ (ml·min^{-1})	Control	271 (16)	274 (29)	266 (30)	280 (17)
	Cooling	300 (19)	420 (49)[a]	411 (32)[a]	379 (38)[a]
Thermal sensation (au)	Control	3.0 (0.2)	4.3 (0.2)[a]	4.4 (0.3)[a]	4.3 (0.4)[a]
	Cooling	3.0 (0.2)	1.3 (0.2)[a,c]	0.8 (0.3)[a,c]	0.7 (0.2)[a,c]
Thermal discomfort (au)	Control	1.4 (0.2)	1.3 (0.4)	1.0 (0.0)	1.0 (0.0)
	Cooling	1.4 (0.2)	3.1 (0.3)[a,c]	3.0 (0.4)[a,c]	2.9 (0.4)[a,c]

[a] Significant difference from baseline
[b] Significant difference from immediate prior time
[c] Significant difference from control water immersion at the same time

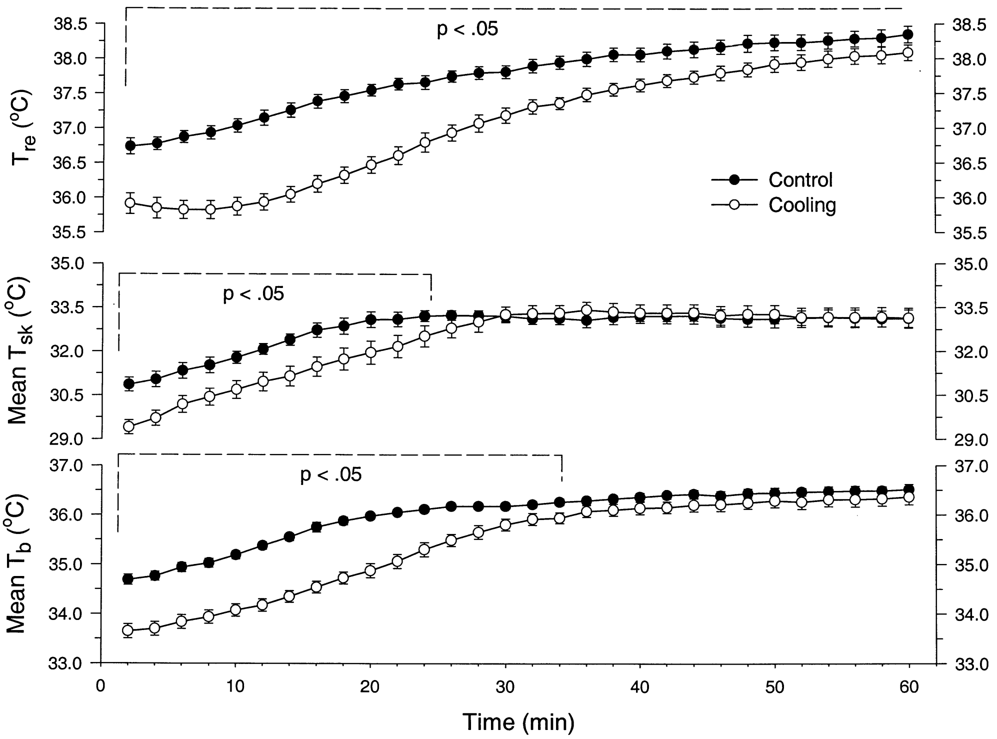

Fig. 1. Mean (SEM) effects of 60 min of submaximal cycling after cooling or control water immersion treatments on rectal temperature (T_{re}), mean skin temperature (Mean T_{sk}), and mean body temperature (Mean T_b). *Values within the brackets* are significantly different between cooling and control treatments

Oxygen uptake increased during cool water immersion compared to baseline level, and by the end of 30 min of immersion there was an approximately 80 ml·min^{-1} difference in oxygen uptake. There were, however, no treatment differences (i.e. cooling compared to control, $P>0.10$) in oxygen uptake observed during water immersion (see Table 1). There were significant increases ($P<0.005$) in both oxygen uptake and heart rate with exercise duration. However, no differences ($P>0.45$) were observed between treatments (i.e. control and cooling) during the 60 min of exercise in oxygen uptake. Heart rate was significantly lower only at min 5 of exercise after cooling (see Fig. 2). Oxygen pulse significantly decreased ($P<0.001$) with exercise duration, but was unchanged ($P>0.40$) during exercise between control or cooling water immersion (see Fig. 2).

Heat storage and transfer

The treatment by immersion in cooling water significantly ($P<0.001$) removed more body heat than the control treatment (a difference of about 720 kJ between treatments). During exercise the cooling treatment significantly ($P<0.001$) allowed the storage of more body heat (a difference of about 670 kJ between treatments) than did the control treatment. The overall S, however, was no different ($P<0.20$) between the entire control and cooling protocols (see Fig. 3). The rate of S was rapid during the first 20 min of exercise after both treatments (see Table 2). Significantly ($P<0.05$) higher rates of S were observed during exercise after cooling compared to control between min 30 and 40 of exercise. Differences in rate of S were large (more than 150 W·m^2) between treatments, especially at min 30 of exercise (see

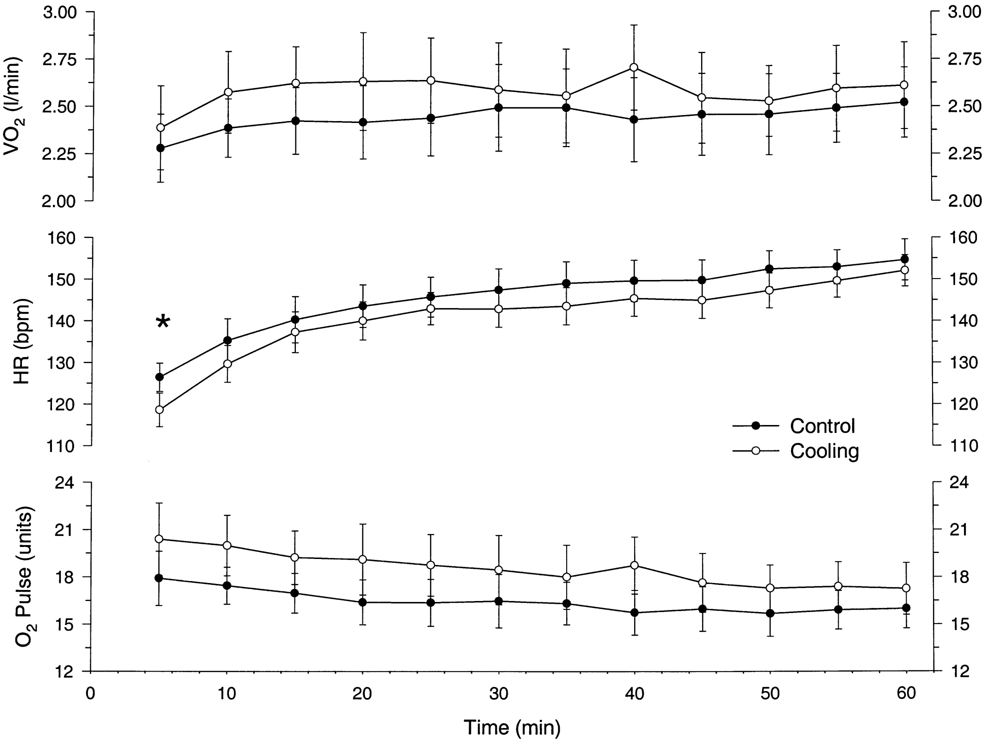

Fig. 2. Mean (SEM) effects of 60 min of submaximal cycling after cooling or control treatments on oxygen uptake ($\dot{V}O_2$), heart rate (*HR*), and oxygen pulse (*O_2 Pulse*). *Significant difference between cooling and control treatments at the $P < 0.05$ level

Table 2). Dry heat transfer was significantly ($P < 0.05$) lower during exercise after cooling for the first 20 min of exercise (see Table 2).

Sweating responses

Sweat rates were significantly lower (about 250 ml·h^{-1}; $P < 0.001$) during exercise after cooling compared to the control treatment (Fig. 4). The mean time of onset of sweating was also significantly delayed ($P < 0.005$) during exercise after cooling by approximately 20 min (see Fig. 4). However, the internal temperature at which sweating began was no different ($P > 0.50$) between treatments [T_{re} of 37.04 (0.03) and 37.08 (0.04)°C for control and cooling treatments, respectively].

Subjects' perceptions

The RPE increased progressively and significantly ($P < 0.001$) during exercise, but no differences ($P > 0.55$) were noted between exercise after the cool or control water treatments (see Table 2). Thermal sensation significantly ($P < 0.005$) increased (i.e. there were warmer sensations) during the control water immersion and significantly ($P < 0.001$) decreased (i.e. cooler sensations) during immersion in cool water. Throughout the immersion in water, thermal sensations were significantly ($P < 0.001$) colder (i.e. lower values for thermal sensation) during the cooling treatment compared to the control (see Table 1). During exercise, thermal sensation significantly ($P < 0.001$) increased (i.e. there were warmer sensations) following both treatments. Differences in thermal sensation between treatments were apparent during the first 20 min of exercise (see Table 2). None of the subjects reported thermal discomfort during the control water immersion, but during immersion in cool water the subjects reported significant ($P < 0.001$) increases (i.e. they became more uncomfortable) in thermal discomfort throughout the immersion relative to baseline values or to the corresponding time during the control treatment (see Table 1). During exercise, thermal discomfort significantly ($P < 0.01$) increased (i.e. the subjects became more uncomfortable) with exercise after the control treatment, while no increases ($P > 0.05$) occurred during exercise after the

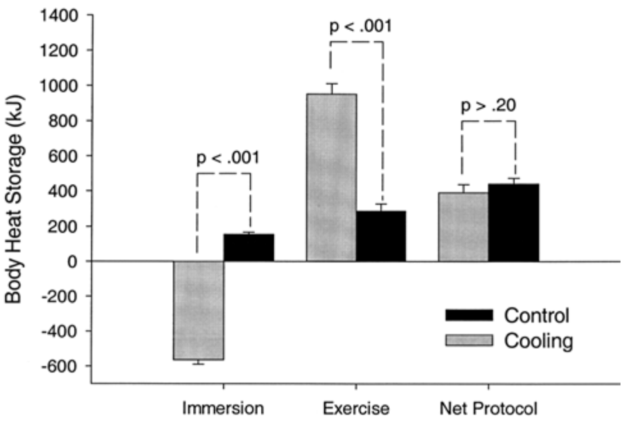

Fig. 3. Calculated mean (SEM) body heat storage during water immersion, submaximal cycling, and the net change across the entire protocol for cooling and control treatments. *Brackets* and corresponding *P* values indicate paired differences

Table 2. Effect of prior water immersion condition on mean (SEM) rate of heat storage, rate of dry heat transfer (i.e. radiant and convective heat flux), thermal sensation, sweat sensation, thermal discomfort, and rating of perceived exertion (*RPE*); during 60 min of exercise at 60% maximal oxygen uptake. *au* arbitrary units. Significance was accepted at the $P < 0.05$ level

Variable	Condition	10 min	20 min	30 min	40 min	50 min	60 min
Heat storage rate ($W \cdot m^2$)	Control	113 (15)	172 (16)[a]	47 (13)[a]	35 (12)	18 (6)	16 (6)
	Cooling	95 (13)	182 (22)[a]	201 (22)[b]	67 (9)[a,b]	39 (9)	12 (8)[a]
Dry heat transfer ($W \cdot m^2$)	Control	79 (2)	86 (2)[a]	89 (2)	90 (2)	89 (2)	89 (2)
	Cooling	73 (2)[b]	81 (3)[a,b]	91 (2)	91 (3)	90 (3)	90 (3)
Thermal sensation (au)	Control	5.6 (0.2)	6.3 (0.2)[a]	6.8 (0.3)[a]	7.1 (0.2)	7.1 (0.2)	7.0 (0.2)
	Cooling	3.9 (0.5)[b]	5.7 (0.2)[a,b]	6.4 (0.2)[a]	6.7 (0.3)	6.9 (0.3)	7.0 (0.3)
Sweat sensation (au)	Control	2.6 (0.2)	3.6 (0.2)[a]	4.0 (0.3)	4.0 (0.3)	4.1 (0.2)	4.3 (0.2)[a]
	Cooling	1.5 (0.2)[b]	2.6 (0.2)[a,b]	3.6 (0.2)[a]	4.0 (0.3)[a]	4.4 (0.3)	4.4 (0.3)
Thermal discomfort (au)	Control	2.3 (0.3)	2.8 (0.2)	2.8 (0.3)	3.0 (0.4)	3.4 (0.4)	3.3 (0.4)
	Cooling	2.6 (0.2)	2.6 (0.4)	2.9 (0.3)	3.1 (0.2)	3.1 (0.2)	3.3 (0.2)
RPE (au)	Control	13.1 (0.6)	14.0 (0.7)[a]	14.5 (0.7)	15.3 (0.8)[a]	15.6 (0.9)	16.0 (0.8)[a]
	Cooling	13.0 (0.7)	13.9 (0.7)[a]	14.6 (0.6)[a]	15.0 (0.7)	15.1 (0.6)	15.8 (0.7)

[a] Significant difference from immediate prior time

[b] Significant difference from control water immersion at the same time

cooling treatment. No differences ($P > 0.20$) were observed between treatments in thermal discomfort during exercise (see Table 2). The sensation of sweating significantly ($P < 0.001$) increased (i.e. greater sweating) during exercise following both treatments. During exercise after the cooling treatment, participants reported less sweating (i.e. a lower sweat sensation score) compared to exercise after the control treatment, until 20 min of exercise (see Table 2).

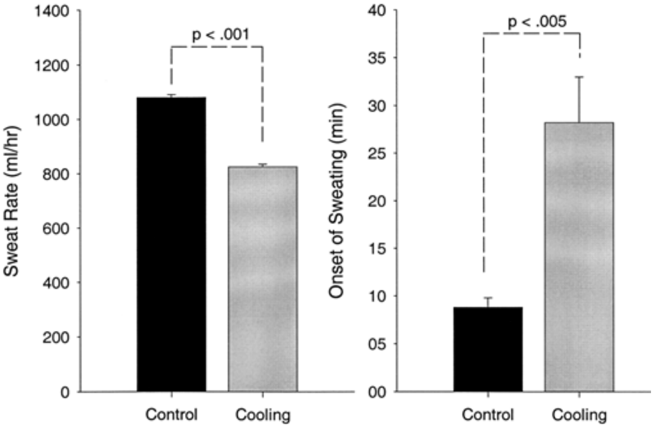

Fig. 4. Mean (SEM) total sweat rate and time of onset of sweating during submaximal cycling following cooling and control treatments. *Brackets* and corresponding *P* values indicate paired differences

Discussion

The major conclusions from this study are that cooling the lower-body by immersion in water created a heat debt prior to exercise that:

1. Allowed greater *S* during exercise
2. Decreased reliance on dry heat transfer and sweating during exercise
3. Resulted in lower T_{re} throughout the exercise
4. More than doubled the time needed during exercise for a 0.5°C increase in internal temperature to occur

These thermal regulatory effects were accomplished without significant differences in heat production during water immersion or higher metabolic rates during exercise between treatments. During exercise, subjects sensed themselves to be cooler and to sweat less after cooling with no differences being observed in discomfort or the effort of exercise. Hence, this study provided evidence of the beneficial physiological and perceptual effects of this simple, economical method of pre-exercise cooling for individuals exercising at submaximal intensities. This information is especially important for individuals or patients who are limited in their activities by increases in internal temperature and *S*, such as heat-sensitive multiple sclerosis patients.

As mentioned in the introduction, techniques for precooling are numerous, with a wide array of observations being reported. Precooling techniques used in the past have included a single exposure to cold air (Kruk et al. 1990; Lee and Haymes 1995), double cold air exposures (Hessemer et al. 1984; Olschewski and Bruck 1988), cold water sprays (Drust et al. 2000), whole-body water immersion (Bergh and Ekblom 1979; Bolster et al. 1999; Booth et al. 1997; Gonzalez-Alonso et al. 1999), torso only water immersion (Marsh and Sleivert 1999), and lower-body water immersion (White et al. 2000). The results from these studies are variable and difficult to compare because of the different cooling techniques and methods of inducing thermal loads. However, precooling techniques that involve a 0.25–1.0°C decrease in internal temperature (with special care being taken to ensure that the treatment does not markedly increase metabolic heat production) generally lead to increases in exercise performance (if the performance would have been limited by heat loads) and decreases in the factors associated with thermal stress.

A major difference between the present study and previous precooling studies concerns the duration and intensity of the exercise. The exercise portion of this protocol was steady-state, submaximal in nature. The majority of previous research in this area has involved maximal graded exercise or exercise at a fixed intensity until fatigue. The maximal exercise protocol is important for assessing questions of exercise performance, but thermal regulatory responses become more difficult to interpret. In this study the exercise intensity was 60% of maximal oxygen uptake, maintained for 60 min in T_a of 21.3 (0.20)°C. This extended duration of exercise allowed the identification of the time course of the responses to lower-body precooling. These unique aspects of the present study make the conclusions more applicable to submaximal indoor activities or to exercise training, rather than exercise performance.

During exercise, the time it took to increase T_{re} by 0.5°C from baseline temperature was more than doubled following cooling compared to the control treatment. The time to increase internal temperature by 0.5°C is important for individuals experiencing sensitivity to heat, such as patients having multiple sclerosis (Petajan and White 1999). It has been demonstrated that increases in internal temperature of as little as 0.5°C can cause blocks in nerve conduction and increase symptoms, thus limiting physical function in these patients (Guthrie and Nelson 1995). For these individuals, exercise is difficult because small increases in internal temperature can occur quickly. Because exercise is a vital part of health and function for these patients (Petajan et al. 1996; Petajan and White 1999), strategies need to be developed that will allow exercise without increasing internal temperature above the usual levels. Previously, we indicated that precooling increased function after 30 min of exercise in patients having multiple sclerosis; however, in the previous study, the mechanisms of the response, treatment and thermal comfort, or thermoregulatory effector responses were not studied (White et al. 2000).

During pre-exercise water immersion, T_{re} decreased slightly from baseline in both treatments (i.e. control and cooling). This minimal change in internal temperature during the water immersion treatment, especially during the cooling treatment, suggested strong peripheral vasoconstriction of the lower limbs and countercurrent heat exchange between deep arteries and veins of the legs (Bazett 1949). Although the majority of the cooling effect was seen in the transition between water immersion and exercise, the change in T_c did not fully manifest itself until min 6–8 of exercise. This afterdrop in temperature is often described in rewarming procedures after accidental hypothermia and has seemed to be heightened by exercise (Giesbrecht and Bristow 1998). The T_{re} afterdrop in this study was fairly large at approximately 0.80°C. The total decrease in T_{re} was 1.00°C, which was similar to earlier observations (White et al. 2000). It is of interest that T_{re} remained lower through the 60 min of exercise following the cooling treatment. At the end of the 60 min of cycling after the cooling treatment, T_{re} was still 0.25°C lower than after the control treatment. Decreases in exercise T_{re} have been observed in other studies, however, the effect has not persisted throughout the exercise duration as observed in this study. The extended effect of T_{re} in this study was probably due to the lower exercise intensity and thus the exercise-induced thermal load.

The mean T_{sk} was 6.8°C lower immediately after water immersion in the cooling compared to the control treatments; however, by the 2nd min of exercise, values were about 1.60°C different. The mean T_{sk} remained lower after cooling compared to the control treatment until min 24 of exercise. Thereafter, similar gradients between the skin and the ambient air temperatures were observed in the two treatments. Although the cooling was of the lower-body, the results are consistent with respect to time of the decreased mean T_{sk} observed when precooling is by immersion of the whole body (Booth et al. 1997).

Metabolic rate and net mechanical efficiency were unchanged after the cooling treatment, indicating similar heat productions in the two protocols during cycling exercise. However, it is unknown whether net mechanical efficiency would be altered by precooling in other, more complex, movements such as running. Consistent with earlier observations using whole-body precooling, the treatment by precooling of the lower-body resulted in lower heart rates initially during exercise (Booth et al. 1997; Lee and Haymes 1995; Olschewski and Bruck 1988). However, this effect was very transient. In this study O_2 pulse was unchanged during exercise after cooling. Previous work using whole-body precooling has reported higher O_2 pulses during exercise, probably as a result of the higher oxygen uptakes seen during exercise following precooling compared to control treatments (Hessemer et al. 1984; Lee and Haymes 1995; Olschewski and Bruck 1988). These higher metabolic heat productions, however, might not be beneficial, as they indicate increased heat production during the precooling treatment.

In the present study, the cooling treatment created a significant negative S of about 560 kJ. We believe that the best method of expressing the effect of treatment is as an amount of S (i.e. in kilojoules) instead of as a rate (e.g. in watts per meter squared). Although the rate of S is very useful, it makes comparisons between studies and treatments more difficult because of varying durations of precooling and exercise among the studies. The larger negative S during cool water immersion in the present study allowed a greater S during exercise. Nevertheless, this greater negative S after the cooling treatment did not alter the total amount of heat stored over the entire protocol when compared to the control treatment. The rate of S during exercise after cooling was as much as four times as great as after the control treatment. This greater S and rate of S meant that less heat needed to be dissipated from the body during exercise after cooling, compared to the control condition.

During the first 20–30 min of exercise after precooling, there was a reduced neural drive to dissipate heat as seen by the lower sweat rates and lower dry heat transfers. Other investigations have reported that precooling results in lower sweat rates during steady-state exercise, but not maximal exercise (Olschewski and Bruck 1988). The lack of an effect of precooling on sweat rate during maximal exercise has probably been due to the method of measuring sweat rate (i.e. pre- post-losses of mass) and variable exercise durations used in these studies. In the current study, there was a decrease in absolute sweat rate observed which allowed a fluid savings of 255 ml following the cooling treatment compared to the control.

The threshold for sweating has previously been identified to occur at a lower internal temperature after precooling when compared to a control condition (Olschewski and Bruck 1988). The current study did show a delay in the onset of sweating in terms of exercise time but no difference in the internal temperature at which sweating occurred during exercise after cooling. Differences between these results could have arisen from differing precooling treatments, ambient exercise conditions, or measurements of internal temperature. The lack of a change in the threshold for sweating, however, does seem to fit better with effector mechanisms of central thermoregulatory control rather than suggesting that precooling changes the temperature set-point or works via a short-term habituation mechanism. However, this question remains open.

The RPE exercise intensity was unaltered in this study. This observation is similar to that of Booth et al. (1997) but different to that of White et al. (2000). The subjects in the latter study, however, consisted of patients suffering from multiple sclerosis who were experiencing a worsening of their heat related symptoms. These symptoms (e.g. footdrop) can interfere with normal movement patterns and therefore with the perception of the difficulty of a period of exercise.

The current study provides the most detailed evaluation of thermal comfort and discomfort during and after precooling to date. The results provide evidence that this particular cooling treatment is well tolerated, although viewed as uncomfortable during cooling. The thermal sensations of being cooler and sweating less persisted for the first 20 min of exercise. This time course was similar to changes in mean T_{sk}. This relationship seems consistent with mean T_{sk} being a major input to the overall concept of thermal sensation and comfort (Hardy 1968).

Limitations

In the current study, mean T_b was estimated using the Burton equation wherein T_{re} is assigned a weighting factor of 0.65 and mean T_{sk} is assigned a weighting factor of 0.35 (Burton 1935). Although the use of other equations to calculate mean T_b (e.g. $0.8 \cdot T_{re}$ and 0.2 mean T_{sk} or $0.9 \cdot T_{re}$ and 0.1·mean T_{sk}) would slightly alter the mean T_b value, they would not affect the interpretations of the data. In fact, the use of either of the other two equations would result in a heavier weighting effect of T_{re} on the calculation of mean T_b, making the precooling effect appear to last even longer than the reported duration in this study.

Skin blood flow is heterogeneous in nature in both glabrous and non-glabrous skin. Therefore, any index of mean T_{sk} is only an approximation of skin surface temperature. As in other precooling studies (Booth et al. 1997; Lee and Haymes 1995), the four-site equation by Ramanathan (1964) was used in this study. This mean T_{sk} weighting equation compared well (i.e. correlation coefficient of 0.98) to mean T_{sk} weighting systems using greater numbers of measurement sites in neutral and warm temperatures (Ramanathan 1964). In the present study, water immersion was to the level of the iliac crest, which meant that the two leg sites were exposed to water while the two upper body sites were not (i.e. neutral air temperatures). The authors know of no study which examines the calculation of mean T_{sk} under these unique conditions. Therefore, some caution must be used when referring to mean T_{sk} under these conditions. Although this was a limitation, each subject was exposed to both treatments, and the same mean T_{sk} sites and weighting equation was used for all comparisons.

Conclusions

The precooling treatment created a negative S and decreased T_{re}, mean T_{sk}, and mean T_b, which allowed the body to store more heat during submaximal exercise. This, combined with the observation that heat production and net metabolic efficiency during exercise were unaltered, indicated that there was a lower reliance on heat dissipation mechanisms during exercise. The well-tolerated nature of the cooling treatment, which can be carried out in a bathtub using cold tap water, should have a broader application than other precooling treatments. Immersion of the lower-body in water is an effective precooling technique as demonstrated by the greater time during exercise before internal temperature rises 0.5°C above the baseline level. This cooling treatment may have unique importance for individuals or patients who are limited in their activities by increases in internal temperature and S such as heat-sensitive patients suffering from multiple sclerosis.

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