Metabolic, thermoregulatory, and perceptual responses during exercise after lower vs. whole body precooling

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White, Andrea T., Scott L. Davis, and Thad E. Wilson. Metabolic, thermoregulatory, and perceptual responses during exercise after lower vs. whole body precooling. J Appl Physiol 94: 1039–1044, 2003. First published November 8, 2002; 10.1152/japplphysiol.00720.2002.—The purpose of this investigation was to compare the thermoregulatory, metabolic, and perceptual effects of lower body (LBI) and whole body (WBI) immersion precooling techniques during submaximal exercise. Eleven healthy men completed two 30-min cycling bouts at 60% of maximal O2 uptake preceded by immersion to the suprailiac crest (LBI) or clavicle (WBI) in 20°C water. WBI produced significantly lower rectal temperature (T_{re}), mean skin temperature, and mean body temperature for the first 24, 14, and 16 min of exercise, respectively. Body heat storage rates differed significantly for LBI and WBI during immersion and exercise, although no net differences were observed between conditions. For WBI, metabolic heat production and heart rate were significantly higher during immersion but not during exercise. Thermal sensation was significantly lower (felt colder) and thermal discomfort was significantly higher (less comfortable) for WBI during immersion and exercise. In conclusion, WBI and LBI attenuated T_{re} increases during submaximal exercise and produced similar net heat storage over the protocol. LBI minimized metabolic increases and negative perceptual effects associated with WBI.

body temperature; water immersion; metabolic heat production; body heat storage

Exercise-induced increases in metabolic heat load considerably challenge temperature homeostasis and may ultimately impair physical work performance (20). Precooling is a strategy used to decrease the temperature of a large tissue mass, thereby creating a “heat sink” before exercise and/or environmentally induced thermal exposure. The beneficial effects of precooling include thermoregulatory, circulatory, and performance benefits (4, 12, 16, 21). By creating a greater body heat storage ($S$) capacity, precooling delays the onset of heat dissipation mechanisms by lengthening the time required to reach sweat threshold (21). In effect, precooling increases the reserve for heat storage, allowing more work to be accomplished before a given increase in core temperature ($T_c$) is reached (25, 26). As a consequence of reducing or delaying the need to dissipate heat, precooling may result in less competition for blood flow between the skin and working muscles during exercise in the heat, thus resulting in less cardiovascular strain.

Several investigators have demonstrated clear benefits of precooling as a means to improve exercise performance in healthy individuals (4, 12, 16, 21), whereas other investigators have reported that precooling had no effect or actually decreased performance (2, 3, 7, 15). Lower body cool water immersion before physical activity has also been helpful in minimizing heat-related decrements in physical function and fatigue in heat-sensitive individuals with multiple sclerosis (MS) (25). Discrepancies in the precooling literature are likely due to varying cooling methods and experimental ambient conditions and to varying exercise loads and population characteristics.

The most effective precooling strategy would maximize the physiological benefits of decreased body temperature ($T_b$) (creation of a heat sink, delay of heat dissipation mechanisms) while minimizing the disadvantages of an “adverse” environment [increased metabolic heat production (M), physical discomfort]. The purpose of this investigation was to compare the effects of two water immersion precooling techniques on thermoregulatory and metabolic responses during exercise-induced heat stress. We hypothesized that lower body immersion (LBI), a treatment that our laboratory has shown to be well tolerated, would be as effective a precooling treatment as whole body immersion (WBI) by delaying the time until a given temperature increase is reached during subsequent submaximal exercise (25). Although there have been several studies that have examined thermoregulatory responses to whole body precooling as well as physiological responses to maximal exercise after precooling, we are aware of no direct comparisons of WBI and LBI precooling techniques on thermoregulatory and metabolic responses during a constant submaximal work rate. A

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submaximal work rate may more practically represent daily activities for average individuals, as opposed to maximal trials performed on highly fit individuals in stressful environments. Furthermore, LBI represents a more practical and accessible method of precooling for individuals with mobility constraints and very little tolerance for increases in Tc, such as many MS patients.

METHODS

Subjects

Eleven healthy men (subject characteristics in Table 1) volunteered to participate. Data were collected in a dry temperate climate (~22°C, ~20% relative humidity, and elevation ~1,300 m). The protocol was approved by the University of Utah Human Subjects Review Board, and all subjects provided written, informed consent.

Measurements

Temperature. Skin temperature (Tsk) was measured by attaching banjo-type surface temperature probes (Yellow Springs Instruments) to the calf, thigh, chest, and arm. Rectal temperature (Tre) was measured via general use thermistor (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. Heart rate was monitored continuously by using a heart rate monitor (Polar). Oxygen consumption (Vo2) was measured by using indirect calorimetry via an automated metabolic cart (ParvoMedics).

Participant perception. The Borg 6-20 point scale of rating of perceived exertion (RPE) was used to determine the participants’ perception of exercise intensity. Nine-point thermal sensation (0 = very cold to 5 = very hot), five-point thermal discomfort (1 = comfortable to 5 = intolerable), and five-point sweating sensation scales (1 = not at all to 5 = maximally) were used to determine the participants’ thermal comfort during the protocol (8).

Calculations

Temperature calculations. Four Tsk sites were used and weighted according to the following equation: mean of mean Tsk = (0.3Tsk chest + Tsk arm) + 0.2(Tsk thigh + Tsk calf) (23). Mean Tb was calculated via the following weighting system: mean Tb = (0.65.Tc) + (0.35.meanTsk), where Tc is indexed by Tb (5).

S. S was estimated via the following formula: S = 0.97(mass - (ΔTb/Δt)AD), where ΔTb is the change in mean body temperature, Δt is the change in time, and AD is body surface area (in m2) (13).

M. M was calculated according to the following formula (10): M = [0.23(R) + 0.77(5.873/vo2)·(60/AD)], where R is respiratory exchange ratio.

RESULTS

Temperature

There were significant treatment effects observed for Tsk during the immersion phase, with mean Tsk being lower during the immersion phase (P < 0.001) than during the recovery phase (P < 0.003). However, the significant differences in Tsk were not maintained during the exercise phase, where Tsk was lower during exercise after LBI compared to WBI (P < 0.001). Similarly, mean Tb was lower during exercise after LBI compared to WBI (P < 0.009) throughout exercise. After WBI, mean Tb was significantly lower than LBI for the first 24 min of exercise (P < 0.05, post hoc Tukey’s test). Mean Tad and mean Tb were also lower during exercise after WBI compared with LBI, but the treatment differences were no longer significant after 14 min (mean Tad) and 16 min (mean Tb) of exercise.

Thermoregulatory Responses

During immersion, significant time and time x treatment (LBI vs WBI) effects were observed for Tre (P < 0.001). Post hoc analysis indicated that, during WBI, Tre was significantly lower than baseline at minutes 24–30 (Fig. 1).

Protocol

Each participant reported to the laboratory three times over the course of the experiment: for a pretest session and for two randomly ordered precooling trials of either LBI or WBI. Each session was separated by 1 wk and was performed at the same time of day. During the pretest session, physical characteristics were measured and subjects performed a maximal graded exercise test on a Monarch cycle ergometer to determine maximal O2 uptake (Vo2 max). The work rate corresponding to 60% Vo2 max was calculated and used for the subsequent submaximal exercise trials described below.

Each precooling trial consisted of four 30-min phases: baseline, immersion, exercise, and recovery. Each phase was separated by 10 min for subject and instrument transition. During the baseline period, each subject, dressed in shorts and shoes, rested on a reclining chair in a thermostatically controlled environment (22°C, 20% relative humidity). During WBI and LBI, subjects were seated in cool water (20°C), immersed to the level of the clavicle and iliac crest, respectively. The exercise phase consisted of cycling at a work rate corresponding to 60% Vo2 max in an environmental chamber at 30.3 ± 0.2°C and 31.9 ± 0.7% relative humidity. After exercise, subjects rested in a semireclined position in a thermoneutral environment throughout the recovery phase.

Statistics

Descriptive statistics (means ± SE) are reported for dependent variables. Two-way (treatment vs. time) ANOVAs with repeated measures were used to evaluate thermoregulatory responses during each experimental phase. When significant main effects were observed, post hoc Tukey’s analyses were performed to determine where treatment and/or time differences existed.

Table 1. Subject characteristics

| Age, yr | 25 ± 2 |
| Height, cm | 180 ± 8 |
| Weight, kg | 78.0 ± 10.6 |
| BSA, m² | 1.97 ± 0.16 |
| Vo2max, ml·kg⁻¹·min⁻¹ | 52.5 ± 5.9 |

Values are means ± SD. BSA, body surface area; Vo2max, maximal O2 uptake.
phases. However, during immersion, \( M \dot{\theta} \) was nearly twice as high for WBI compared with LBI (132 ± 15 vs. 71 ± 5 W/m², respectively, at minute 30; \( P < 0.01 \)) (Table 2). Heart rate was also significantly higher during WBI compared with LBI (\( P < 0.05 \)) (Table 2). No significant treatment (WBI vs. LBI) differences were observed for \( M \dot{\theta} \) or heart rate during exercise (Table 3).

Subjective Responses

There were no differences between treatments for sweat sensation, thermal sensation, or thermal discomfort during baseline and recovery phases. Thermal sensation throughout immersion was significantly lower (felt colder) during WBI compared with LBI (\( P < 0.05 \)). Similarly, thermal discomfort was significantly higher (less comfortable) for WBI throughout immersion (\( P < 0.005 \)) (Table 2).

During the exercise phase, sweat sensation scores increased significantly after both treatments. After WBI, sweat sensation scores were significantly lower than those after LBI through 20 min of exercise (\( P < 0.05 \)). Treatment differences were no longer apparent at 30 min for sweat sensation (Table 3).

There were no significant treatment differences in RPE scores during exercise. However, RPE scores increased significantly (\( P < 0.05 \)) during exercise after both precooling treatments.

DISCUSSION

Our laboratory has previously demonstrated, in a small number of MS patients, that LBI precooling is tolerable, effective, and practical for use (25). Because many MS patients experience symptom worsening with small (0.5°C) increases in internal temperature, an effective precooling technique could have profound effects on preserving physical function during conditions that increase internal temperature. In turn, precooling could facilitate greater participation in health-enhancing activities such as exercise and rehabilitation programs.

To date, the relative effectiveness of WBI and LBI precooling on thermoregulatory and metabolic responses during submaximal exercise has not been investigated. A direct comparison of the effects of these two immersion techniques during subsequent submaximal exercise performance was necessary to prescribe appropriate precooling recommendations for clinical populations.

The present study demonstrated that LBI and WBI precooling techniques 1) prevented excessive \( T_{re} \) increases during subsequent submaximal exercise by lowering initial \( T_{re} \) and 2) resulted in similar net \( S \) changes over the experimental protocol. WBI produced a greater cooling effect compared with LBI, as demonstrated by significantly lower \( T_{re} \) during the first 24 min of exercise. However, this larger cooling effect was accompanied by higher \( M \dot{\theta} \) and less thermal comfort during cooling. LBI also produces significant physiological benefits but minimizes the metabolic and perceptual effects resulting from WBI.

During 30 min of cool-water immersion, heat in the body core was presumably conserved by peripheral vasoconstriction in the immersed extremities, reducing the skin-to-water temperature gradient. The magnitude of heat loss during WBI was greater due to the larger skin surface area exposed to cooling, as well as greater heat flow from the trunk areas (14). This was demonstrated by a significant reduction in \( T_{re} \) compared with baseline during the last 6 min of immersion. By themselves, these observations would appear to suggest that WBI is a superior precooling method. However, the effectiveness of both precooling techniques became more evident during subsequent exercise when blood circulating through the cooled areas produced significant initial reductions in \( T_{re} \).

During WBI, \( M \dot{\theta} \) increased significantly to a value nearly twice that achieved during LBI (Table 2). This corresponds well to the afferent stimulation provided...
by the two immersion techniques (11), with WBI exposing approximately twice as much skin surface area. In cold air, increasing M may preserve core temperature but cannot offset heat loss in cool or cold water (6, 17). M during LBI was somewhat higher than reported during thermoneutral conditions (~73 W/m² during LBI compared with ~40–49 W/m²) (19). Using the Weir (24) equation, Lee et al. (17) reported slightly lower M during resting immersion to the hip and neck in 15 and 25°C than was observed in the present study. The differences between hip- and neck-level immersion at 15 and 25°C were ~140 and ~40 W/m², respectively (17). At 15°C, increased M during neck-level immersion was likely due to greater thermal afferent input and shivering induced by larger decreases in Tc. In the present study, a difference of ~60 W/m² between WBI and LBI was observed, which is consistent with the findings of Lee et al. for the 25°C immersion condition.

Smaller increases in M during LBI may be beneficial for some clinical populations. For example, MS patients have limited physical capacity for work due to accumulated disability and abnormal fatigue, which is worsened by increased Tb. The increase in M induced by WBI is somewhat counterproductive to the purpose of precooling for individuals with MS, which is to facilitate achievement of physical activities.

Differential responses in temperature and metabolism between LBI and WBI resulted in significant differences in S rates over the course of the experiment. WBI resulted in a significantly greater rate of heat loss during immersion and a significantly greater positive S rate during exercise compared with LBI (Fig. 2). However, the net effect of both immersion techniques was essentially the same when the negative and positive changes were balanced for the entire experiment. This is in contrast to our laboratory's previous work using the same exercise protocol preceded by either LBI precooling or no cooling (25). Although precooling resulted in greater rates of negative and positive S during immersion and exercise, respectively, net S over the course of the experiment was significantly greater for the no-cooling condition (25). This higher heat gain corresponded to significantly higher Tc in the noncooled condition for the duration of exercise.

Table 2. Effect of lower body and head-out whole body cold-water immersion on core body temperature, heart rate, metabolic heat production, thermal sensation, and thermal discomfort at 10, 20, and 30 min of immersion

<table>
<thead>
<tr>
<th>Variable</th>
<th>Condition</th>
<th>10 min</th>
<th>20 min</th>
<th>30 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tc, °C</td>
<td>WBI</td>
<td>37.02 ± 0.06</td>
<td>36.90 ± 0.10</td>
<td>36.67 ± 0.15*</td>
</tr>
<tr>
<td></td>
<td>LBI</td>
<td>37.06 ± 0.08</td>
<td>37.05 ± 0.09</td>
<td>36.92 ± 0.11</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>WBI</td>
<td>75 ± 1.5*</td>
<td>72 ± 1.4*</td>
<td>70 ± 1.2*</td>
</tr>
<tr>
<td></td>
<td>LBI</td>
<td>67 ± 2.2</td>
<td>65 ± 1.9</td>
<td>63 ± 1.6</td>
</tr>
<tr>
<td>M, W/m²</td>
<td>WBI</td>
<td>136 ± 13*</td>
<td>130 ± 13*</td>
<td>132 ± 15*</td>
</tr>
<tr>
<td></td>
<td>LBI</td>
<td>74 ± 3</td>
<td>73 ± 5</td>
<td>71 ± 5</td>
</tr>
<tr>
<td>Thermal sensation</td>
<td>WBI</td>
<td>1.1 ± 0.3*</td>
<td>0.6 ± 0.3*</td>
<td>0.7 ± 0.3*</td>
</tr>
<tr>
<td></td>
<td>LBI</td>
<td>2.0 ± 0.2</td>
<td>1.9 ± 0.2</td>
<td>1.9 ± 0.2</td>
</tr>
<tr>
<td>Thermal discomfort</td>
<td>WBI</td>
<td>3.1 ± 0.2*</td>
<td>3.3 ± 0.2*</td>
<td>3.3 ± 0.2*</td>
</tr>
<tr>
<td></td>
<td>LBI</td>
<td>2.2 ± 0.2</td>
<td>2.2 ± 0.3</td>
<td>2.4 ± 0.3</td>
</tr>
</tbody>
</table>

Values are means ± SE. LBI, lower body immersion; WBI, head-out whole body immersion; Tc, rectal temperature; HR, heart rate; M, metabolic heat production. *Significant treatment differences, P < 0.05.

Table 3. Effect of lower body and head-out whole body precooling on heart rate, rating of perceived exertion, metabolic heat production, sweat sensation, thermal sensation, and thermal discomfort during supramaximal exercise at a workload corresponding to 60% VO₂max

<table>
<thead>
<tr>
<th>Variable</th>
<th>Condition</th>
<th>10 min</th>
<th>20 min</th>
<th>30 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR, beats/min</td>
<td>WBI</td>
<td>139 ± 3</td>
<td>155 ± 3</td>
<td>164 ± 3</td>
</tr>
<tr>
<td></td>
<td>LBI</td>
<td>135 ± 2</td>
<td>150 ± 3</td>
<td>160 ± 3</td>
</tr>
<tr>
<td>RPE, 9-20 point scale</td>
<td>WBI</td>
<td>13.1 ± 0.6</td>
<td>14.1 ± 0.6</td>
<td>15.1 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>LBI</td>
<td>12.8 ± 0.4</td>
<td>14.4 ± 0.6</td>
<td>15.4 ± 0.6</td>
</tr>
<tr>
<td>M, W/m²</td>
<td>WBI</td>
<td>419 ± 15</td>
<td>396 ± 38</td>
<td>439 ± 14</td>
</tr>
<tr>
<td></td>
<td>LBI</td>
<td>382 ± 13</td>
<td>412 ± 22</td>
<td>432 ± 20</td>
</tr>
<tr>
<td>Sweat sensation</td>
<td>WBI</td>
<td>1.4 ± 0.2*</td>
<td>2.8 ± 0.2*</td>
<td>3.8 ± 0.2*</td>
</tr>
<tr>
<td></td>
<td>LBI</td>
<td>1.9 ± 0.2</td>
<td>3.2 ± 0.2</td>
<td>4.1 ± 0.2</td>
</tr>
<tr>
<td>Thermal sensation</td>
<td>WBI</td>
<td>4.9 ± 0.4</td>
<td>5.8 ± 0.3</td>
<td>6.2 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>LBI</td>
<td>5.4 ± 0.2</td>
<td>6.3 ± 0.1</td>
<td>6.7 ± 0.1</td>
</tr>
<tr>
<td>Thermal discomfort</td>
<td>WBI</td>
<td>1.7 ± 0.2</td>
<td>2.3 ± 0.1</td>
<td>2.7 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>LBI</td>
<td>2.0 ± 0.2</td>
<td>2.5 ± 0.3</td>
<td>2.9 ± 0.3</td>
</tr>
</tbody>
</table>

Values are means ± SE. RPE, rating of perceived exertion. *Significant treatment differences, P < 0.05.
exercise, an overall $T_{re}$ increase of $\sim 1^\circ C$ was observed after both WBI and LBI. This magnitude of change in $T_{re}$ is consistent with other studies that have utilized the same relative workload (25, 26). Because precooling does not appear to alter the slope of temperature increases during 30 min of submaximal exercise (Fig. 3), the reduction in $T_{re}$ produced by precooling largely determines the net $T_{re}$ increase above normal baseline temperature. In a study that compared LBI precooling to no cooling in MS patients, LBI produced an after-drop of 0.8°C (25). As in the present study, 30 min of exercise at 60% $V_{\text{O}2\text{max}}$ resulted in overall $T_{re}$ increases of 0.9°C for LBI and noncooled conditions. During the noncooled trial, a $T_{re}$ of 0.5°C above baseline was reached at 22 min of exercise. In contrast, LBI produced no net increase in $T_{re}$ at the end of 30 min of exercise (25).

Similarly, in healthy men, LBI precooling produced a reduction in $T_{re}$ of 1°C, noted by 6–8 min of exercise at 60% $V_{\text{O}2\text{max}}$. The time required to produce a 0.5°C $T_{re}$ increase was 33 min for the precooled condition compared with 15 min for the noncooled condition (26). In the present study, WBI and LBI produced similar delays in the time to increase $T_{re}$ by 0.5°C (24 and 28 min of exercise for LBI and WBI, respectively). Variability in the studies cited above was due to differing immersion temperatures (16°C for Ref. 26, and 20°C for the present study) and ambient conditions during exercise (21–23°C for Ref. 26, and 30°C for the present study). Immersion temperature for the present study was based on observations suggesting WBI in 16°C water would not be tolerated well (4, 18).

Throughout WBI, thermal sensation scores were significantly lower (colder) and thermal discomfort scores were significantly higher (more uncomfortable) compared with LBI. Although the differences in thermal comfort and thermal sensation were statistically significant, one might question the practical interpretation of a one-point difference on these perceptual scales. However, this small perceptual benefit combined with the greater accessibility of LBI (which can be accomplished in a regular bath tub by using tap water) may indicate the use of LBI precooling as a practical means to delay heat stress during subsequent physical activity, be it exercise or activities of daily living.

During exercise, subjective measures assessed after WBI and LBI were similar. There were no treatment differences in RPE throughout exercise. This observation is consistent with Booth et al. (4) and Wilson et al. (26), but it differs from that of White et al. (25). This discrepancy is likely due to differing subject populations. The latter study examined MS patients who experienced symptom worsening with increased $T_c$. Greater difficulty with motor control and other neurological signs may explain the increased perception of effort.

Sweat sensation was significantly lower after WBI through minute 20 of exercise, suggesting that sweat production may have been reduced. This is consistent with our laboratory’s previous work that demonstrated that precooling significantly delayed onset of sweating and led to decreased sweat loss during 60 min of submaximal exercise (26).
Limitations

In the present study, mean $T_b$ was estimated by the Burton equation (5), wherein $T_{re}$ is given the weighting factor of 0.65, and mean $T_{sk}$ is given the weighting factor of 0.35. The Burton equation was used because of the higher weighting of $T_{sk}$, because during a cold stress, especially during water immersion, skin temperature is more important in thermal balance. Although other weighting systems (e.g., 0.8 $T_{re}$ and 0.2 mean $T_{sk}$ or 0.9 $T_{re}$ and 0.1 mean $T_{sk}$) used in the literature slightly alter the calculated mean $T_b$ value, using them would not affect the interpretation of the data comparing the two treatments.

Water immersion to the level of the neck alters body fluid balance and cardiovascular responses while in the water (9). However, we did not observe the characteristic baroreceptor-mediated decrease in heart rate due to increases in central blood volume during water immersion to the level of the neck because of the overriding effect of the 20°C water on increasing M. It is therefore unlikely that differences in depth of water immersion per se had profound effects on the thermal or cardiovascular responses during exercise after water immersion.

Conclusion

In conclusion, WBI and LBI attenuated $T_c$ increases during submaximal exercise by producing a reduction in $T_{re}$, with WBI producing a slightly greater cooling effect. Both treatments produced similar net $\dot{S}$ over the entire protocol. However, LBI minimized metabolic increases and negative perceptual effects associated with WBI. Because of its similar thermal effect, reduced metabolic and perceptual effects, and ease of use, LBI should be the preferred precooling method for patient populations that demonstrate impaired physical function with increased internal temperature.

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