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Arngrímsson, Sigurbjörn Á., Darby S. Petitt, Matthew G. Stueck, Dennis K. Jorgensen, and Kirk J. Cureton. Cooling vest worn during active warm-up improves 5-km run performance in the heat. *J Appl Physiol* 96: 1867–1874, 2004. First published December 29, 2003; 10.1152/japplphysiol.00979.2003.—We investigated whether a cooling vest worn during an active warm-up enhances 5-km run time in the heat. Seventeen competitive runners (9 men, maximal oxygen uptake = 66.7 ± 5.9 ml·kg^{-1}·min^{-1}; 8 women, maximal oxygen uptake = 58.0 ± 3.2 ml·kg^{-1}·min^{-1}) completed two simulated 5-km runs on a treadmill after a 38-min active warm-up during which they wore either a T-shirt (C) or a vest filled with ice (V) in a hot, humid environment (32°C, 50% relative humidity). Wearing the cooling vest during warm-up significantly ($P < 0.05$) blunted increases in body temperature, heart rate (HR), and perception of thermal discomfort during warm-up compared with control. At the start of the 5-km run, esophageal, rectal, mean skin, and mean body temperatures averaged 0.3, 0.2, 1.8, and 0.4°C lower; HR averaged 11 beats/min lower; and perception of thermal discomfort (5-point scale) averaged 0.6 point lower in V than C. Most of these differences were eliminated during the first 3.2 km of the run, and these variables were not different at the end. The 5-km run time was significantly lower ($P < 0.05$) by 13 s in V than C, with a faster pace most evident during the last two-thirds of the run. We conclude that a cooling vest worn during active warm-up by track athletes enhances 5-km run performance in the heat. Reduced thermal and cardiovascular strain and perception of thermal discomfort in the early portion of the run appear to permit a faster pace later in the run.

body temperature; cardiovascular strain; exercise; running; thermoregulation

ATHLETIC COMPETITION OFTEN takes place during the summer months in hot climates. It is well established that high ambient temperature is detrimental to endurance performance such as distance running (1, 12, 21, 24, 30, 32). A rise in core temperature (T_c) during exercise and heat stress to a critical level of ~40°C causes fatigue (13, 21, 25). Hyperthermia during moderately prolonged, strenuous exercise increases cardiovascular strain (33), reduces maximal oxygen uptake ($\dot{V}O_{2\,max}$), and increases relative metabolic strain (2), and it detrimentally affects central nervous system functioning (6, 26–28).

Laboratory studies have shown that lowering T_c before exercise (precooling) can delay fatigue during constant-rate exercise (13, 20) or increase the work performed in a given period of time (4, 13). Precooling increases the heat storage possible before a critical temperature that limits performance is reached. However, despite considerable research suggesting the effectiveness of precooling for improving performance of moderately prolonged exercise (22), there is little evidence that precooling could be used to improve performance of athletes in competition. Most studies on the effects of precooling have used methods of precooling (water immersion, cold air) that would not be feasible for athletes immediately before competition. Moreover, studies have not incorporated a period of active warm-up, which most athletes believe is important to optimize neuromuscular function, into the protocol. And finally, studies have not assessed the effects of precooling on high-level competitive athletes by using a measure of performance that mimics their performance in competition.

The purpose of this study was to determine the effect of wearing a cooling vest during a typical, active warm-up on simulated 5-km run performance in moderately hot, humid ambient conditions in male and female middle- and long-distance runners. Associated physiological and perceptual effects of wearing a cooling vest were also studied to provide insight into the mechanism underlying performance enhancement, if it occurs. It was hypothesized that *1*) 5-km run performance after a warm-up while wearing a cooling vest is enhanced compared with a run after a warm-up when no cooling vest is worn; *2*) there is no difference in the effect of wearing a cooling vest during warm-up between male and female runners; and *3*) improved performance is associated with reduced skin temperature (T_{sk}) and T_c, reduced heart rate (HR), and reduced thermal discomfort during the early portion of the simulated 5-km run but with the same values for these measures at exhaustion.

METHODS

Subjects. Seventeen healthy, male ($n = 9$) and female ($n = 8$) competitive collegiate and club middle- and long-distance runners were recruited as subjects. Their physical characteristics are presented in Table 1. There were four 800-m, two 1,500-m, five 5,000-m, five 10,000-m, and one marathon specialists. The men and women had averaged 102.3 ± 17.7 and 76.4 ± 21.8 km/wk of running for the last 7.7 ± 5.2 and 6.8 ± 2.4 yr, respectively, and were accustomed to exercising in a hot environment. The study was approved by the University's Institutional Review Board, and written, informed consent was obtained before testing.

Experimental design. A repeated-measures experimental design in which subjects served as their own control was used. After preliminary testing of $\dot{V}O_{2\,max}$ and body composition (skinfolds), the subjects completed simulated 5-km runs on a treadmill in an environmental chamber (32°C, 50% relative humidity) under two experimental conditions in counterbalanced order: *1*) an experimental condition in which subjects wore a cooling vest with ice packs during warm-up (V) and *2*) a control condition in which subjects wore a regular T-shirt

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Table 1. *Subject characteristics*

Variable	Men (n = 9)	Women (n = 8)
Age, yr	23.4±4.4	22.1±2.2
Height, cm	178.6±4.4*	167.7±5.5
Mass, kg	67.7±4.2*	55.9±4.3
Body fat, %	7.3±2.0*	17.8±3.3
$\dot{V}O_{2\,max}$, l/min	4.50±0.31*	3.24±0.25
$\dot{V}O_{2\,max}$, $ml \cdot kg^{-1} \cdot min^{-1}$	66.7±5.9*	58.0±3.2
$\dot{V}O_{2\,max}$, $ml \cdot kg\ FFM^{-1} \cdot min^{-1}$	72.0±7.0	70.6±4.9
Best 5-km run time, min	15.5±0.8*	17.9±1.1

Values are means ± SD; n, no. of subjects. $\dot{V}O_{2\,max}$, maximal oxygen uptake; FFM, fat-free mass. *Gender difference significant, $P < 0.05$.

during warm-up (C). All subjects were tested at the same time of the day to minimize the effects of circadian rhythm on HR and T_c, and at least 2 days passed between testing of the same subject.

The cooling vest (Neptune Wetsuits Australia, Smithfield West, Australia) was developed by the Australian Institute of Sport for use by Australian Olympic Athletes. The vest is made of neoprene and has eight pockets for ice packs (450–500 ml each): two on the chest, two on the stomach, two over the shoulder blades, and two on the lower back. The subjects were told we were investigating whether wearing a cooling vest during warm-up helped (because of cooling) or hindered (because of the weight of the vest) running performance.

Test protocol. Subjects reported to the laboratory after a 3-h fast, but they were well hydrated. They were instructed not to consume alcohol or drugs 48 h before testing, not to consume caffeine 12 h before testing, and to drink water and other noncaffeinated beverages liberally. Urine specific gravity ranged from 1.001 to 1.0265, and there was no difference between conditions or between men and women. On the morning of the test, subjects completed a 24-h history questionnaire designed to determine adherence to pretest instructions. Then, subjects measured their nude body weight; they inserted rectal and esophageal thermistors for measurement of T_c; thermistors for measurement of T_{sk} were attached, with care to ensure the back T_{sk} probe was not in contact with the ice packs in the cooling vest; and a strap containing the electrodes and transmitter for a HR monitor was placed around the chest. Finally, subjects put on the cooling vest or the T-shirt and entered the environmental chamber.

The subjects then completed a 38-min warm-up that was typical of what they would do before competition, followed by a simulated 5-km run. HR, rectal temperature (T_{re}), esophageal (T_{es}), and T_{sk} were recorded every 5 min during the first 25 min of the warm-up and every minute thereafter during the warm-up and the simulated runs. Perceptual measures [ratings of perceived exertion (RPE), thermal sensation] were measured at rest, after 30 min of warm-up, immediately before the simulated run, and at 1.6, 3.2, and 5 km during the simulated run. No metabolic data were collected during warm-up, but oxygen uptake ($\dot{V}O_2$) and other metabolic variables of interest were measured during the performance run and recorded at 1.6, 3.2, and 5 km. A metabolic cart (Vmax 29, SensorMedics) was used to measure the metabolic variables over a sampling period of 30 s. Two consecutive 30-s values were averaged for all metabolic measures. Immediately after the simulated run, a finger-stick blood sample was obtained and analyzed for lactate. Then, subjects dried off and measured their nude body weight to determine the amount of weight loss.

Test procedures. To elicit $\dot{V}O_{2\,max}$, subjects ran to exhaustion on a treadmill at a constant speed, with the grade increasing 2% every 2 min following a protocol described in detail elsewhere (2). In short, a graded exercise test to exhaustion was administered, after which all subjects rested for 20 min and then ran to exhaustion at a grade 2% higher than the grade at the end of the graded test. Using this protocol, all subjects demonstrated a plateau in $\dot{V}O_2$.

The warm-up protocol performed before the two simulated 5-km run trials was the same and designed to simulate a warm-up distance runners might do before a race. After subjects had been prepped and had entered the chamber, they mounted the treadmill and resting measures were collected. Then, they performed a 10-min warm-up at their normal warm-up speed (established during the preliminary testing), followed by 10 min of stretching exercises. Next, the subjects ran again for 10 min on the treadmill at a little faster (~1.6 km/h) pace than during the first 10 min. Then, four 20- to 30-s strides at just below and just above the simulated race pace were conduced with 30–40 s of rest. Finally, the subjects took off the cooling vest or the T-shirt, they inserted a mouthpiece for collection of metabolic data, and prerun measurements were recorded. The only protocol difference between the conditions was a slightly slower speed (~0.8 km/h) in V during warm-up to compensate for the extra metabolic work done in that condition due to the weight of the vest.

The speed during the simulated 5-km run was initially set to the average speed that corresponded to the 5-km run time the runners felt they were capable of running at the time. This judgement was based on times they had run recently and their personal best time, taking into account their recent training and current level of fitness. Thereafter, the speed was increased or decreased as requested by the runners. Distance was determined from the product of treadmill belt length and number of revolutions. Subjects ran until the requisite revolutions (counts) were completed. The runners were informed of distance completed every 400 m and were given 400-m splits, but they were not told the total time elapsed during the run or their 5-km performance times until the study was completed.

During the warm-up, the subjects drank water ad libitum. The amount of water ingested during the first condition was recorded, and they were asked to drink the same amount of water during the other condition. The water ingested ranged from 0.0 to 0.68 liter, and there was no difference between conditions or between men and women. The time of ingestion was not controlled, and because the water was at tap temperature, it caused some fluctuations in T_{es}.

T_{re} was measured with a Yellow Springs Instruments (YSI) thermistor (model 4491E, YSI, Dayton, OH) inserted 12 cm beyond the anal sphincter. T_{es} was measured by using a YSI thermistor (model 4491E) inserted through the nasal cavity and into the esophagus a distance equal to one-fourth of the standing height. T_{sk} was measured with YSI thermistors (model 409B). All temperature probes were connected to YSI telethermometers (models 44TD or 4600). The accuracy of the thermistors was verified by using water baths of various temperatures before use.

HR was measured using a Polar Vantage XL HR monitor (model 145900, Polar Electro, Woodbury, NY). Blood lactate was measured with a YSI 2300 STAT plus lactate-glucose analyzer. RPE was measured by the Borg 15-point category scale (5). Thermal sensation was measured on a 5-point category scale (1 corresponding to "neutral" and 5 corresponding to "as hot as possible") modified from Gagge et al. (11). Body weight was measured with an electronic scale (model FW-150KA1, A&D, Tokyo, Japan). Body density was estimated from the sum of seven skinfolds measured with Lange calipers and age (16, 17), and percent body fat was estimated by using the Siri (34) equation.

Calculations. Mean T_{sk} ($\bar{T}_{sk}$) was calculated according to the formula of Burton (7)

$$\bar{T}_{sk} = 0.5 \cdot T_1 + 0.36 \cdot T_2 + 0.14 \cdot T_3$$

where T_1, T_2, and T_3 are back, thigh, and forearm T_{sk}, respectively. Mean T_b ($\bar{T}_b$) was calculated from T_{re} and $\bar{T}_{sk}$ with the following formula

$$\bar{T}_b = 0.87 \cdot T_{re} + 0.13 \cdot \bar{T}_{sk}(3)$$

Rate of heat storage (S) was calculated as

$$S\ (W/m^2) = [(0.97 \cdot m) \cdot (\Delta\bar{T}_b/\Delta t)]/A_D(10)$$

where 0.97 is the specific heat of the body in ($W \cdot h {}^{\circ}C^{-1} \cdot kg^{-1}$), m is the body mass (in kg), $\Delta\bar{T}_b/\Delta t$ is the change in $\bar{T}_b$ over time (in °C/h),

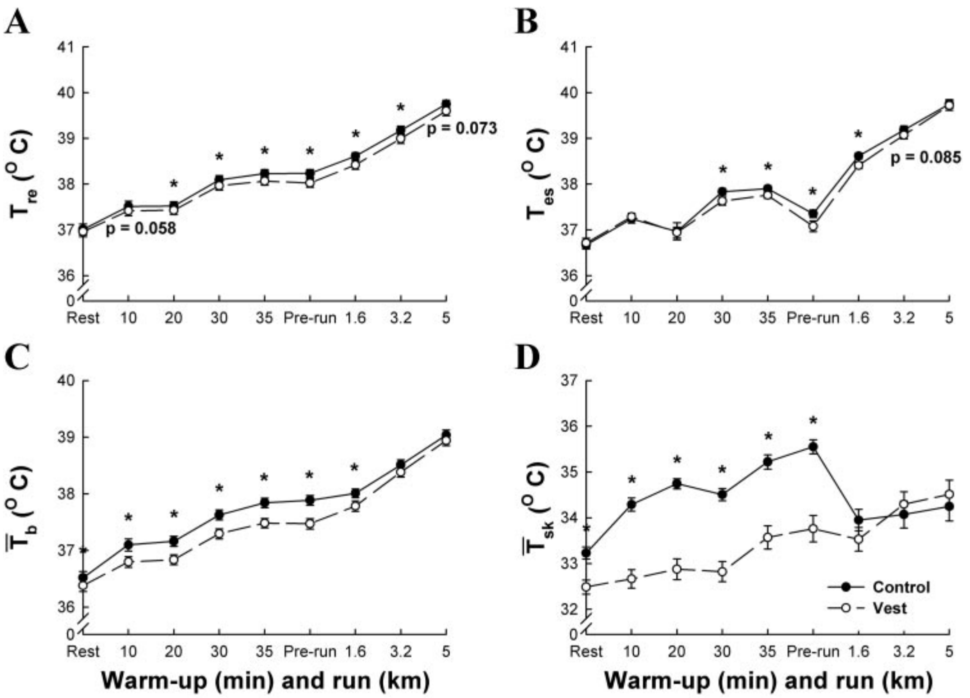

Fig. 1. Rectal (T_{re}; *A*), esophageal (T_{es}; *B*), mean body ($\bar{T}_b$; *C*), and mean skin ($\bar{T}_{sk}$; *D*) temperatures during the warm-up and the simulated 5-km run. Values are means ± SE. Vest, experimental condition in which subjects wore a cooling vest with ice packs during warm-up. Control, condition in which subjects wore a regular T-shirt during warm-up. *Significant difference between conditions, $P < 0.05$.

and A_D is the DuBois surface area (10). Metabolic heat production (*M*) was calculated with the formula of Ravussin et al. (31)

$$M\ (\mathrm{W/m^2}) = (\{4.686 + [(\mathrm{RER} - 0.707)/0.293] \cdot 0.361\} \cdot \dot{V}_{O_2} \cdot 69.78)/A_D$$

where 4.686 is the energy value of 1 liter of O_2 at nonprotein respiratory exchange ratio (RER) of 0.707 in kcal/l, 0.707 is the RER when only fat is oxidized, 0.293 is the difference between the RER for carbohydrate and fat oxidation, 0.361 is the difference in energy value of 1 liter of O_2 between RER of 1 and RER of 0.707, and 69.78 is a constant (to change kcal/min to W). An approximate estimate of work done during horizontal running (8% of energy expenditure) was subtracted from *M* (37). Heat exchange by convection (*C*) was calculated with the following formula

$$C\ (\mathrm{W/m^2}) = h_c(T_{db} - \bar{T}_{sk})(19)$$

where T_{db} is dry-bulb temperature and h_c is the convective coefficient for heat exchange (8.3 $W \cdot m^{-2} \cdot {}^\circ C^{-1}$) (19). Heat exchange by radiation (*R*) was calculated similarly

$$R\ (\mathrm{W/m^2}) = h_r(T_r - \bar{T}_{sk})(19)$$

where h_r is the radiative heat exchange coefficient calculated with the formula from Kenney (19)

$$h_r\ (\mathrm{W/m^2/{}^\circ C}) = 5.67 \cdot 10^{-8} \cdot 0.99 \times \{0.72 \cdot [(T_r + 273)^4 - (\bar{T}_{sk} + 273)^4]/(T_r - \bar{T}_{sk})\}$$

where 5.67×10^{-8} is the Stephan Boltzmann constant (in $W \cdot m^{-2} \cdot {}^\circ K^{-1}$) (19), 0.99 is the constant emissivity of the skin (19), 0.72 is the projected area of the body (19), and in both these formulas T_r is assumed to be the same as T_{db} (19). Because body weight was measured only before the warm-up and after the 5-km run, evaporative heat loss (*E*) during the run was calculated by difference using the heat balance equation, assuming no conduction. Finally, heat stored, metabolic heat produced, heat exchanged by convection and radiation, and heat lost by evaporation (in J/m^2) during the run were calculated by multiplying *S*, *M*, *C*, *R*, and *E* by run time (in s).

Statistical analysis. Statistical analyzes were done with SPSS 10 for Windows (SPSS, Chicago, IL). Data are reported as means ± SD. An independent samples *t*-test was used to determine significance of difference between men and women for the preliminary tests ($\dot{V}_{O_2\,max}$ and skinfolds). For the experimental tests, a two-way (gender × condition) mixed-model repeated-measures ANOVA was used to determine the significance of differences between means by condition, gender, and their interaction. Four isolated gender × condition interactions were statistically significant (HR at rest, $\bar{T}_{sk}$ before the 5-km run, *S* at 3.2 km, and T_{es} at 5 km), but in three of these cases the pattern of the gender differences was the same (e.g., V lower than C in men and women). For T_{es} at 5 km, the differences between conditions were in the opposite direction but were very small. Otherwise, there were no significant gender × condition interactions. Therefore, the data for men and women were combined. A two-tailed α level of 0.05 was used for all significance tests.

RESULTS

Warm-up. The cooling vest reduced thermal and cardiovascular strain during the warm-up (Figs. 1 and 2, and Table 2).

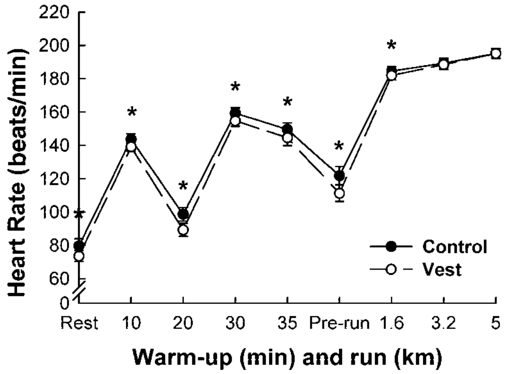

Fig. 2. Heart rate during warm-up and the simulated 5-km run. Values are means ± SE. *Significant difference between conditions, $P < 0.05$.

Table 2. *Cardiovascular, temperature, and perceptual variables at the start of the 5-km run*

Variable	Condition	
	Control (n = 17)	Vest (n = 17)
T_{es}, °C	37.4±0.4*	37.1±0.5
T_{re}, °C	38.2±0.4*	38.0±0.4
$\bar{T}_{sk}$, °C	35.6±0.6*	33.8±1.2
$\bar{T}_b$, °C	37.9±0.4*	37.5±0.4
$\dot{V}O_2$, l/min	0.51±0.08	0.52±0.14
HR, beats/min	122±22*	111±20
RER	1.04±0.05	1.04±0.04
RPE	8.8±2.0†	7.7±2.0
Thermal discomfort	3.1±0.7*	2.5±0.8

Values are means ± SD; *n*, no. of subjects. T_{es}, esophageal temperature; T_{re}, rectal temperature, $\bar{T}_b$, mean body temperature; $\bar{T}_{sk}$, mean skin temperature; $\dot{V}O_2$, oxygen uptake; HR, heart rate; RER, respiratory exchange ratio; RPE, ratings of perceived exertion. *Conditions significantly different, $P < 0.05$. † $P = 0.071$.

$\bar{T}_{sk}$ was significantly lower throughout the warm-up in V than C. This primarily reflected the effect of the back T_{sk} probe under the vest. At the start of the 5-km run, $\bar{T}_{sk}$ was lower in V than C by 1.79 ± 1.20°C. The difference in T_{re} between V and C increased progressively during warm-up, becoming statistically significant after 20 min. At the start of the 5-km run, T_{re} was 0.21 ± 0.20°C lower in V than C. T_{es} responded essentially the same as T_{re}, only with more fluctuation due to the fluid ingested between *minutes 10* and *20* and immediately before the start of the 5-km run. At the start of the 5-km run, T_{es} was 0.28 ± 0.35°C lower in V than C. $\bar{T}_b$ increased during warm-up as a function of increased T_{re} and $\bar{T}_{sk}$, and it was 0.42 ± 0.25°C lower in V than in C at the start of the 5-km run. Heat stored was significantly lower by 32.0 ± 27.5 kJ/m^2 or 19% during the warm-up in V than in C. HR was lower in V than C throughout the warm-up, averaging 11 ± 9 beats/min lower at the start of the 5-km run. On the basis of ratings of thermal comfort, the runners felt cooler after 30 min of warm-up in V, a feeling that still existed at the start of the 5-km run. They also perceived the warm-up as being easier at 30 min into the warm-up ($P < 0.05$, data not shown), although difference between the conditions in RPE (1.1 ± 2.3) did not remain statistically significant ($P = 0.071$) at the start of the run.

The 5-km run performance. The 5-km run time was significantly less in V than C by 1.1% (Table 3). The magnitude of difference was similar for men and women as indicated by the lack of a significant gender × condition interaction effect in the two-way ANOVA. Twelve runners ran faster after warming up in V, with the remaining 5 running faster in C. For the combined group of men and women, the time difference was 0 s at 1.6 km, 7 s at 3.2 km, and 13 s at 5 km. Improved performance occurred primarily in the middle and at the end of the run.

Responses during the 5-km run. Although $\dot{V}O_2$ was slightly higher in V during the 5-km-run (0.03–0.04 l/min), the difference was not statistically significant (Table 4). Runners maintained a pace that averaged 81–85% of $\dot{V}O_{2\,max}$. HR was lower by 3 ± 5 beats/min at 1.6 km into the run, but there was no significant difference thereafter. Runners averaged 93–100% of the maximal HR determined during pretesting. RER values were above 1.0 throughout the run. Although RPE tended to be lower on average in V than C by 0.5–0.7 during the first 3.2 km, those differences were not statistically significant. RPE values were similar at the end of the 5-km run. Blood lactate concentration at the end of exercise was ~6 mmol/l with no statistically significant difference between conditions. The mean values for lactate, HR, RER, and RPE suggest the runners gave a similar, maximal effort under both conditions. There was no difference between conditions in preexercise weight, but significantly more weight was lost in C than V.

Table 3. *Individual and group 5-km split and total run times during the simulated 5-km run*

Subject No.	Distance					
	1.6 km		3.2 km		5 km	
	Control	Vest	Control	Vest	Control	Vest
1	298	293	623	611	1,015	984
2	328	323	657	660	1,023	1,044
3	300	302	600	603	930	937
4	333	332	669	665	1,075	1,054
5	343	343	699	672	1,078	1,026
6	332	323	678	652	1,042	1,031
7	346	342	697	685	1,097	1,073
8	354	355	714	717	1,122	1,136
9	313	313	627	618	980	959
10	388	388	807	805	1,323	1,319
11	399	389	801	778	1,249	1,207
12	390	389	798	793	1,265	1,249
13	382	393	827	827	1,339	1,366
14	345	365	713	737	1,136	1,155
15	388	386	799	794	1,300	1,285
16	393	389	793	783	1,260	1,229
17	395	403	801	791	1,255	1,225
Group						
Men	328±20	325±20	662±39*	653±37	1,040±61	1,027±61
Women	385±17	388±11	793±34	788±26	1,266±62	1,255±67
Total	355±35	355±36	724±76*	717±76	1,147±130*	1,134±132

Values are given in s. Group values are means ± SD. *Subjects 1–9* are men; *subjects 10–17* are women. *Conditions significantly different, $P < 0.05$.

Table 4. *Metabolic, cardiovascular, and perceptual responses during the simulated 5-km run*

	Distance					
	1.6 km		3.2 km		5 km	
Variable	Control	Vest	Control	Vest	Control	Vest
$\dot{V}O_2$, l/min	3.29±0.52	3.32±0.58	3.17±0.56	3.23±0.62	3.27±0.62	3.31±0.61
%$\dot{V}O_{2\,max}$	84.7±6.2	85.3±5.3	81.3±6.3	82.8±6.9	83.5±5.3	84.7±6.4
HR, beats/min	185±11*	182±11	189±12	189±12	195±12	195±12
%HR_{max}	94.5±2.8*	93.1±3.2	97.0±3.2	96.5±3.1	99.9±3.2	99.9±3.1
RER	1.04±0.05	1.04±0.04	1.05±0.05	1.07±0.04	1.06±0.05*	1.08±0.05
RPE	14.0±1.9	13.3±1.5	16.1±1.8	15.6±1.8	19.0±1.2	18.8±1.3
Thermal discomfort	3.4±0.9	3.1±0.9	4.0±0.7	3.9±0.7	4.6±0.5	4.4±0.7
Lactate, mmol/l					5.7±1.4	6.1±1.9
Weight loss, kg†					1.2±0.4*	1.0±0.4

Values are means ± SD. %$\dot{V}O_{2\,max}$, percentage of $\dot{V}O_{2\,max}$, %HR_{max}, percentage of maximal HR (from preliminary testing). *Conditions significantly different, $P < 0.05$. †Calculated across warm-up and 5-km run.

Although $\bar{T}_{sk}$ was significantly lower in V than C at start of exercise, this difference was rapidly eliminated as $\bar{T}_{sk}$ in C decreased 1.6°C during the first 1.6 km. There was no difference in $\bar{T}_{sk}$ at 1.6, 3.2, or 5-km during the run between V and C (Fig. 1). T_{re} was significantly lower at the start of exercise, remained significantly lower during the first 3.2 km, but was not significantly lower (0.15 ± 0.33°C; $P = 0.073$) at the end of the run in V compared with C. The increase in T_{re} during the run was not significantly different in V compared with C. The response of T_{es} was similar to T_{re}, except there was a smaller difference in T_{es} at the end of exercise (0.03 ± 0.28°C). The increase in T_{es} during the run was significantly greater in V (2.64 ± 0.53°C) than in C (2.40 ± 0.35°C). At the end of exercise, T_{es} and T_{re} averaged ~39.7°C (range 38.7–40.7°C). $\bar{T}_b$ was significantly lower at the onset of the 5-km run and at 1.6 km in V than C, but no statistically significant differences were found between the conditions at 3.2 or 5 km. The increase in $\bar{T}_b$ during the run was significantly greater in V (1.47 ± 0.23°C) than in C (1.15 ± 0.26°C). $\bar{T}_b$ was ~39.0°C at the end of the run (range 38.2–39.8°C).

During the 5-km run, *S* increased more rapidly in V than in C. *S* was 66 W/m^2 (150%) greater during the first 1.6 km, 39 W/m^2 (23%) greater during the second 1.6 km, and 16 W/m^2 (11%) greater during the final segment of the run (Table 5). There were only small differences in metabolic heat production and convective and radiative heat loss, and the greater *S* was due to less evaporative heat loss in V than C. Using the heat balance equation to calculate the rate of evaporative heat loss by difference indicates that it was 46 W/m^2 (9%) less during the first 1.6 km, 26 W/m^2 (7%) less during the second 1.6 km, and 12 W/m^2 (3%) less during the final segment of the run. Less evaporative heat loss in V than in C is consistent with the lower measured weight loss (Table 4) during the warm-up and 5-km run in V. Heat stored during the entire run was 41 kJ/m^2 (29%) greater in V than C (Fig. 3).

DISCUSSION

The unique aspect of this study was that it was designed to investigate the feasibility of precooling during warm-up as an ergogenic aid to enhance competitive distance running performance in the heat. Two previous studies have found that precooling improves distance run performance. Lee and Haymes (20) had noncompetitive male runners run to exhaustion at 82% of $\dot{V}O_{2\,max}$ in comfortable laboratory conditions (24°C) after resting 30 min in cold (5°C) air. Run time increased 17% with precooling. Booth et al. (4) investigated the effect of precooling on the maximum distance that could be run in 30 min in a warm environment (31.6°C, 60% relative humidity) in male and female recreational runners after water immersion for 60 min in a cold (23–24°C) water bath. Distance run in 30 min was 304 m (4.2%) greater after precooling.

These studies provide strong evidence that precooling can improve running endurance or distance run in a fixed time, but whether this means that precooling is a useful ergogenic aid for track athletes is unclear. Although resting in cold air or cold water immersion could be used for precooling, it would not be practical because it would make active warm-up, considered by most track athletes to be important to optimize neuromuscular performance, difficult.

Table 5. *Rates of heat exchange during the simulated 5-km run*

	Distance					
	1.6 km		3.2 km		5 km	
Variable	Control (n = 17)	Vest (n = 17)	Control (n = 17)	Vest (n = 17)	Control (n = 17)	Vest (n = 17)
M, W/m^2	609±60	614±71	586±72	597±78	603±80	611±75
R, W/m^2	−13±4*	−8±5	−9±5	−9±5	−10±6	−11±6
C, W/m^2	−23±6*	−14±9	−17±9	−16±9	−18±10	−20±10
E, W/m^2	−529±53*	−483±58	−391±69*	−365±62	−421±69	−409±46
S, W/m^2	44±52*	110±32	168±41*	207±46	154±47	171±55

Values are means ± SD; *n*, no. of subjects. *M*, metabolic heat production rate; *R*, radiative heat exchange rate; *C*, convective heat exchange rate; *E*, evaporative heat loss rate (calculated by difference); *S*, heat storage rate. *Conditions significantly different, $P < 0.05$.

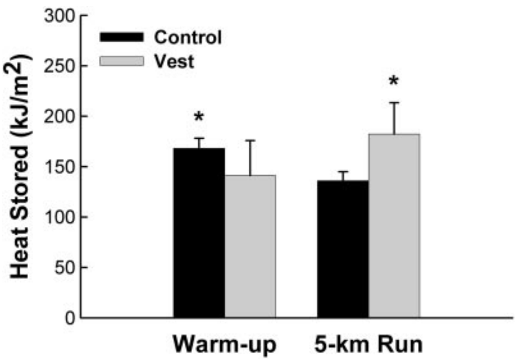

Fig. 3. Heat stored during warm-up and the simulated 5-km run. Values are means ± SE. *Significant difference between conditions, $P < 0.05$.

Our study is the first to investigate whether precooling during a typical, active warm-up before a competitive event is effective in improving performance. The cooling vest we used, designed for Australian Olympic athletes before the Atlanta Olympic games, was effective in blunting the rise in $\bar{T}_b$ during a 38-min active warm-up that mimicked the routine a distance runner might use before competition. At the end of warm-up, T_{re}, $\bar{T}_{sk}$, and $\bar{T}_b$ were reduced by 0.2, 1.6, and 0.3°C during V relative to C. These differences changed only slightly in the 3–4 min between the end of the warm-up and start of the run. Despite the relatively small effects of the vest on $\bar{T}_b$, it reduced body heat storage during warm-up by 19%.

The effect of the cooling vest in blunting the rise in T_c during warm-up was smaller than the effects reported in the two studies discussed above (4, 20) or in most other studies in which those same two methods of precooling, or precooling using a cooling vest with and without thigh cooling in cold air, have improved cycling performance (8, 14, 29). In these studies, the decrease in T_c resulting from precooling ranged from 0.4 to 1.0°C. However, decreased T_c is not necessary for precooling to improve performance. Kay et al. (18) found that progressive precooling for ~1 h by water immersion that decreased $\bar{T}_{sk}$ by 4.4°C and $\bar{T}_b$ by 1.6°C, but did not change T_{re}, significantly improved distance cycled in 30 min by 6%. Our data suggest that only relatively small decreases in $\bar{T}_{sk}$ and $\bar{T}_b$, coupled with a small decrease in T_{re}, also can improve performance.

The disadvantage of the cooling vest as a means of precooling is that it is somewhat heavy (~4.5 kg). The vest does not interfere with running or stretching, but it increases the energy cost of running. We offset this effect by decreasing the speed of running during warm-up in V compared with C so that running elicited the same estimated percent $\dot{V}O_{2\,max}$ in the two conditions. Twelve of 16 runners asked responded that they liked wearing the vest during warm-up better than not wearing it. The reasons they gave were that the they felt cooler and perceived they sweated less. One reported the vest made her feel better overall. Three of the four runners who liked the control condition better complained about the weight of the vest, and one complained about skin irritation caused by the vest rubbing. Two of the runners who stated that they liked the vest better performed better in the control condition, and one of the runners who disliked the vest performed better after warming up in it.

Previous studies investigating the effect of precooling on distance running performance have not used the same type of performance test as encountered in actual competition. They have used time to exhaustion at a constant rate or distance run in a fixed time, which have different end points and cannot be used to reflect the magnitude of improvement in performance that might be expected in track competition. We used a simulated 5-km run on the treadmill to mimic as closely as possible performance on the track but still permit physiological measures that provide insight into the mechanism underlying any performance alteration. The 5-km run times on the treadmill were considerably poorer than the best times the runners had obtained on the track because of the detrimental effects of *1*) breathing into a respiratory one-way valve and corrugated tubing; *2*) having T_{es}, T_{re}, and T_{sk} probes; *3*) running in the heat; and *4*) being without competition. Nevertheless, the results should reflect the magnitude of improvement that might be expected running on a track with comparable ambient conditions.

We studied the effects of precooling on male and female track athletes. No previous studies investigating the effects of precooling on performance have reported data on comparable male and female athletes to determine whether the ergogenic effects are the same. The male and female runners we studied had been training for a comparable number of years, and, although the men averaged more distance in training than the women, their fitness level, as reflected by $\dot{V}O_{2\,max}$ expressed relative to fat-free mass, was the same. We found the physiological and performance effects of wearing cooling vests during warm-up were similar in men and women.

The magnitude of the precooling effect obtained by using the cooling vest, an improvement in time or average speed of 1.1%, seems small. However, a 13-s improvement translates into a 57-m advantage at the average speed run in the vest condition, a large difference in a 5,000-m competition. This magnitude of improvement is similar to the effects of other legitimate practices used by athletes to enhance performance, such as altitude training (35). The percent improvement obtained in other precooling studies have been larger, but this is related in part to the nature of the performance test. Some studies investigating the effect of precooling have used time to exhaustion at a fixed work rate as the criterion measure of performance (13, 20). Hopkins et al. (15) have estimated that for tests to exhaustion at a fixed percent $\dot{V}O_{2\,max}$, the percent change equivalent to the corresponding change in power or speed is estimated by multiplying a constant equal to percent $\dot{V}O_{2\,max}$ divided by 6.4. Thus, for our data on the 5-km run performed at ~84% $\dot{V}O_{2\,max}$, the 1.1% improvement in time or speed is equivalent to a 14.4% change in time to exhaustion. This change was smaller than that reported by Lee and Haymes (20), who found that precooling in cold air that lowered T_{re} 0.37°C before exercise, almost twice the precooling effect obtained in our study, increased time to exhaustion during running on the treadmill at 85% of $\dot{V}O_{2\,max}$ by 21%. Gonzalez-Alonzo et al. (13) reported that precooling by water immersion that decreased T_{es} by 1.5°C, increased time to exhaustion during cycling at 60% of $\dot{V}O_{2\,max}$ by 37%. Booth et al. (4) found that precooling by water immersion that decreased the preexercise T_{re} by 0.7°C increased distance run in 30 min by 304 m or 4%. Thus the performance improvement obtained in our study seems consistent with the degree of precooling.

Precooling during active warm-up improved performance in the 5-km run, which lasted between 15.6 and 22.8 min in our male and female runners. Whether it improves performance in shorter, higher intensity or longer, lower intensity track events is unknown. However, in other studies, precooling has improved performance in tasks requiring all-out efforts as short as 70 s (23) and as long as 60 min (14). These data suggest that performance in track events between ~600 and 10,000 m might be improved through precooling. Logic would suggest that performance in a much longer event such as the marathon probably would not be improved by precooling, because the physiological and perceptual effects are lost in a relatively brief time at the onset of exercise in events in which the work rate is not fixed. Nevertheless, it is possible athletes continue to benefit in the later states of an event after the effects of precooling are eliminated. The upper limit in duration for athletic events that benefit from precooooling remains to be determined.

Although the mechanism through which precooling improves performance in comfortable as well as in hot ambient conditions is not known, it is thought that by reducing the body heat content before exercise, cardiovascular strain is lower, more work can be performed before a critical level of hyperthermia associated with fatigue is reached, and the perceptions of thermal discomfort and effort that may provide cues concerning the highest intensity possible are lower (22). The combination of these effects appears to permit a higher intensity to be maintained during the latter stages of a performance test. In our study, the increases in $\bar{T}_b$, HR, and perception of thermal discomfort during warm-up were blunted by wearing the cooling vest, so they were lower at the start of the 5-km run. These responses to precooling have been observed by others (4, 6, 8, 13, 14, 18, 20, 29) and were expected, although the extent to which they would occur during an active warm-up with the cooling vest used was unknown. Most of these effects of precooling were eliminated by the end of the first 3.2 km, although T_{re} continued to be significantly lower through 3.2 km. Surprisingly, pace during the 5-km run was not substantially greater during the first 1.6 km when the effects of precooling were largest; most of the improvement in performance occurred because of a faster pace maintained later in the run, when the effects of precooling were smaller or not evident. In the 12 runners who performed better in V, an average 17.4% of their improvement occurred in the first one-third (1.6 km) and 55.0% in the second one-third (between 1.6 and 3.2 km) of the run (Table 3). This suggests that these runners started out at a similar pace in both conditions but realized after the first 1.6 km that they could do better and increased the pace. Hence, the largest portion of their improvement in the second one-third of the run. By 3.2 km, most of precooling effects were gone and only 27.6% of the improvement came in the last 1.8 km of the run. Improved performance in the later stages of an exercise test when the precooling effects are least evident has been observed by others (4, 8, 14, 18). Thus the ergogenic effect of precooling on run pace is not directly proportional to magnitude of reduced thermal and cardiovascular strain, and perceptions of thermal discomfort and effort, evident at the time.

One hypothesized mechanism through which precooling may enhance performance is that by lowering the T_c before exercise is begun, greater heat storage is possible during exercise before T_c rises to a critical level that causes fatigue. Considerable research on humans (13, 21, 25) and animals (9, 36) indicates that there is a critical T_c of ~40°C that causes fatigue. At the finish of the 5-km run in V and C, T_{es} and T_{re} averaged ~39.7°C (range 38.7–40.7°C) and, in at least some individuals, were approaching the critical level of hyperthermia associated with fatigue. Unlike studies in which time to exhaustion is the measure of performance, it cannot be suggested that the runners in this study terminated exercise because they may have reached a critical level of hyperthermia. Running in this study was terminated when the runners reached 5 km. Nevertheless, all indications are they had regulated their pace so that they were near the point of exhaustion, and may have been at or near a critical level of hyperthermia, at the end of the run. Thus perceptual cues about the level of hyperthermia, and/or the associated level of cardiovascular strain, could have set the upper limit to the pace the runners were willing or were able to tolerate. In only one of the studies investigating the effect of precooling on performance has T_c appeared to reach a critical level of hyperthermia that caused fatigue (13). In that study, subjects who cycled to exhaustion in the heat (40°C) under precooled, normothermic, and preheated conditions terminated exercise when T_{es} reached 40.1–40.2°C. T_c values in the present study were slightly below those but apparently very close to the critical level of hyperthermia (25). In other studies investigating the effect of precooling under cool (14), normothermic (20), and hot conditions (4, 8), T_c values at the end of the performance tests were lower and apparently not at a critical level of hyperthermia. Because the upper limit of heat storage had not been reached in these studies, it is unlikely that greater heat storage capacity per se was the mechanism precooling improved performance. Rather, other metabolic, cardiovascular, and perceptual factors, affected in part by hyperthermia, probably limited performance and mediated the effects of precooling.

We conclude that wearing a cooling vest during warm-up is effective in blunting increases in $\bar{T}_b$, HR, and perception of thermal discomfort during warm-up and in improving subsequent simulated 5-km run performance in a hot, humid climate in male and female competitive runners. Reduced thermal and cardiovascular strain and perception of thermal discomfort in the early portion of the run appear to make possible a faster pace in the latter portions of the run. More widespread use of precooling to improve track performance in middle- and long-distance races in the heat is warranted.

GRANTS

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REFERENCES

1. **Adams WC, Fox RH, Fry AJ, and MacDonald IC.** Thermoregulation during marathon running in cool, moderate, and hot environments. *J Appl Physiol* 38: 1030–1037, 1975.
2. **Arngrimsson SA, Stewart DJ, Borrani F, Skinner KA, and Cureton KJ.** Relation of heart rate to percent $\dot{V}O_{2\,peak}$ during submaximal exercise in the heat. *J Appl Physiol* 94: 1162–1168, 2003.
3. **Baum E, Bruck K, and Schwennicke HP.** Adaptive modifications in thermoregulatory system of long-distance runners. *J Appl Physiol* 40: 404–410, 1976.
4. **Booth J, Marino F, and Ward JJ.** Improved running performance in hot humid conditions following whole body precooling. *Med Sci Sports Exerc* 29: 943–949, 1997.
5. **Borg G.** The perception of physical performance. In: *Frontiers of Fitness*, edited by Shepard RJ. Springfield, IL: Thomas, 1971, p. 280–294.

6. **Bruck K and Olschewski H.** Body temperature related factors diminishing the drive to exercise. *Can J Physiol Pharmacol* 65: 1274–1280, 1987.
7. **Burton AC.** Human calorimetry. II. The average temperature of the tissues of the body. *J Nutr* 9: 261–280, 1935.
8. **Cotter JD, Sleivert GG, Roberts WS, and Febbraio MA.** Effect of precooling, with and without thigh cooling, on strain and endurance exercise performance in the heat. *Comp Biochem Physiol A* 128: 667–677, 2001.
9. **Fuller A, Carter RN, and Mitchell D.** Brain and abdominal temperatures at fatigue in rats exercising in the heat. *J Appl Physiol* 84: 877–883, 1998.
10. **Gagge AP and Nishi Y.** Heat exchange between human skin surface and thermal environment. In: *Handbook of Physiology. Reactions to Environmental Agents*. Bethesda, MD: Am. Physiol. Soc., 1977, sect. 9, chapt. 5, p. 69–92.
11. **Gagge AP, Stolwijk JAJ, and Hardy JD.** Comfort and thermal sensations and associated physiological responses at various ambient temperatures. *Environ Res* 1: 1–20, 1967.
12. **Galloway SDR and Maughan RJ.** Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. *Med Sci Sports Exerc* 29: 1240–1249, 1997.
13. **Gonzalez-Alonso J, Teller C, Andersen SL, Jensen FB, Hyldig T, and Nielsen B.** Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *J Appl Physiol* 86: 1032–1039, 1999.
14. **Hessemer V, Langusch D, Bruck K, Bodeker RH, and Breidenbach T.** Effect of slightly lowered body temperatures on endurance performance in humans. *J Appl Physiol* 57: 1731–1737, 1984.
15. **Hopkins WG, Hawley JA, and Burke LM.** Design and analysis of research on sport performance enhancement. *Med Sci Sports Exerc* 31: 472–485, 1999.
16. **Jackson AS and Pollock ML.** Generalized equations for predicting body density of men. *Br J Nutr* 40: 497–504, 1978.
17. **Jackson AS, Pollock ML, and Ward A.** Generalized equations for predicting body density of women. *Med Sci Sports Exerc* 12: 175–182, 1980.
18. **Kay D, Taaffe DR, and Marino FE.** Whole-body pre-cooling and heat storage during self-paced cycling performance in warm humid conditions. *J Sports Sci* 17: 937–944, 1999.
19. **Kenney WL.** Heat flux and storage in hot environments. *Int J Sports Med* 19: S92–S95, 1998.
20. **Lee DT and Haymes EM.** Exercise duration and thermoregulatory responses after whole body precooling. *J Appl Physiol* 79: 1971–1976, 1995.
21. **MacDougall JD, Reddan WG, Layton CR, and Dempsey JA.** Effects of metabolic hyperthermia on performance during heavy prolonged exercise. *J Appl Physiol* 36: 538–544, 1974.
22. **Marino FE.** Methods, advantages, and limitations of body cooling for exercise performance. *Br J Sports Med* 36: 89–94, 2002.
23. **Marsh D and Sleivert G.** Effect of precooling on high intensity cycling performance. *Br J Sports Med* 33: 393–397, 1999.
24. **McCann DJ and Adams WC.** Wet bulb globe temperature index and performance in competitive distance runners. *Med Sci Sports Exerc* 29: 955–961, 1997.
25. **Nielsen B, Hales JRS, Strange S, Christensen NJ, Warberg J, and Saltin B.** Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. *J Physiol* 460: 467–485, 1993.
26. **Nielsen B, Hyldig T, Bidstrup F, Gonzalez-Alonso J, and Christoffersen GRJ.** Brain activity and fatigue during prolonged exercise in the heat. *Pflügers Arch* 442: 41–48, 2001.
27. **Nybo L and Nielsen B.** Hyperthermia and central fatigue during prolonged exercise in humans. *J Appl Physiol* 91: 1055–1060, 2001.
28. **Nybo L and Nielsen B.** Perceived exertion is associated with an altered brain activity during exercise with progressive hyperthermia. *J Appl Physiol* 91: 2017–2023, 2001.
29. **Olschewski H and Bruck K.** Thermoregulatory, cardiovascular, and muscular factors related to exercise after precooling. *J Appl Physiol* 64: 803–811, 1988.
30. **Pugh LG, Corbett JL, and Johnson RH.** Rectal temperature, weight losses, and sweat rates in marathon running. *J Appl Physiol* 23: 347–352, 1967.
31. **Ravussin E, Schutz Y, Acheson KJ, Dusmet M, Bourquin L, and Jarvie GJ.** Short-term, mixed-diet overfeeding in man: no evidence for “luxuskonsumption.” *Am J Physiol Endocrinol Metab* 249: E470–E477, 1985.
32. **Robinson S.** Temperature regulation during exercise. *Pediatrics* 32: 691–702, 1963.
33. **Rowell LB.** *Human Circulation: Regulation During Physical Stress*. New York: Oxford University Press, 1986, p. 383–385.
34. **Siri WE.** Body composition from fluid spaces and density: analysis of methods. In: *Techniques for Measuring Body Composition*, edited by Brozek J and A. Henschel. Washington, DC: National Academy of Sciences, 1961, p. 223–244.
35. **Stray-Gundersen J, Chapman RF, and Levine BD.** “Living high-training low” altitude training improves sea level performance in male and female elite runners. *J Appl Physiol* 91: 1113–1120, 2001.
36. **Walters TJ, Ryan KL, Tate LM, and Mason PA.** Exercise in the heat is limited by critical internal temperature. *J Appl Physiol* 89: 799–806, 2000.
37. **Webb P, Saris WH, Schoffelen PF, Van Ingen Schenau GJ, and Ten Horr F.** The work of walking: a calorimetric study. *Med Sci Sports Exerc* 20: 331–337, 1988.