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Heat extraction through the palm of one hand improves aerobic exercise endurance in a hot environment

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Grahn, Dennis A., Vinh H. Cao, and H. Craig Heller. Heat extraction through the palm of one hand improves aerobic exercise endurance in a hot environment. *J Appl Physiol* 99: 972–978, 2005. First published May 5, 2005; doi:10.1152/japplphysiol.00093.2005.—In situations where the accumulation of internal heat limits physical performance, enhanced heat extraction from the body should improve performance capacity. The combined application of local subatmospheric pressure (35–45 mmHg) to an entire hand (to increase blood volume) and a heat sink (18–22°C) to the palmar surface were used to draw heat out of the circulating blood. Subjects walked uphill (5.63 km/h) on a treadmill in a 40°C environment. Slopes of the treadmill were held constant during paired experimental trials (with and without the device). Heat extraction attenuated the rate of esophageal temperature rise during exercise (2.1 ± 0.4° and 2.9 ± 0.5°C/h, mean ± SE, with and without the device, respectively; $n = 8$) and increased exercise duration (46.1 ± 3.4 and 32.3 ± 1.7 min with and without the device, respectively; $n = 18$). Hand cooling alone had little effect on exercise duration (34.1 ± 3.0, 38.0 ± 3.5, and 57.0 ± 6.4 min, for control, cooling only, and cooling, and subatmospheric pressure, respectively; $n = 6$). In a longer term study, nine subjects participated in two or four trials per week for 8 wk. The individual workloads (treadmill slope) were varied weekly. Use of the device had a beneficial effect on exercise endurance at all workloads, but the benefit proportionally decreased at higher workloads. It is concluded that heat can be efficiently removed from the body by using the described technology and that such treatment can provide a substantial performance benefit in thermally stressful conditions.

arteriovenous anastomoses; venous plexus; aerobic capacity; cardiac drift; heat stress

A RISING BODY TEMPERATURE during exercise can be a primary factor limiting performance, especially endurance, in a hot environment (1, 7, 12, 15, 17, 19, 21, 23). Studies have shown that precooling can increase subjects' endurance for exercise or work in a hot environment (see Ref. 16 for review). The effect of precooling is most likely due to creation of a greater heat sink in peripheral tissues for metabolically produced heat (7, 13, 24). Therefore, the effectiveness of precooling is most prominent in endurance events lasting 30–40 min, and 4–16% increases in endurance have been reported (5, 13, 20). Precooling maneuvers that have been used, however, require specialized equipment, such as cold rooms or water baths, and the treatments typically last from 30 min to >1 h. Thus application of such maneuvers is not practical under many circumstances. We have been exploring performance benefits that could be obtained from using a portable device to continuously extract heat from the body core during endurance exercise in a hot environment.

The heat extraction technology takes advantage of adaptations for heat transfer that are features of certain nonhairy skin surfaces. The arteriovenous anastomoses (AVAs) and venous plexuses in the palms of the hands and the soles of the feet are effective mechanisms for heat dissipation when core body temperature rises (3, 4, 9, 10, 17). A device previously described (11) is used to apply a 35- to 45-mmHg subatmospheric pressure to an entire hand to draw blood into the hand and increase the filling of the venous plexus underlying the palmar surface. A heat sink applied to that palm extracts heat and cools the venous blood. In the present study, we used the device in an attempt to slow the rate of core temperature rise of individuals engaged in aerobic exercise in a hot environment.

The hypothesis to be tested in these studies was that manipulation of heat balance by enhancing heat loss from the hand can increase the endurance capacity of individuals exercising at a fixed workload in a hot environment. To test the hypothesis, it was first necessary to establish that use of the heat extraction method during exercise in a hot environment affected core temperature. This was accomplished by measuring esophageal temperature (T_{es}) in a subset of the subject population (only a limited number of subjects would tolerate the esophageal thermocouple probe placement). Besides an increase in core temperature, another concomitant of steady-state aerobic exercise in a hot environment is cardiac drift (see Ref. 6 for review). At the onset of exercise, heart rate rises to an appropriate level for the particular workload. However, as core temperature rises, heart rate also rises, even though the workload is held constant. In the present study, we compared the rates of rise of heart rate with and without heat extraction, and we used a specific heart rate target as the exercise end point for comparisons of endurance. The protocols were designed to address three specific questions: *1*) Does the continuous use of the heat extraction device attenuate core temperature rise during fixed-load exercise? *2*) Does use of the heat extraction device improve fixed-load exercise endurance? *3*) Is the effect of heat extraction on exercise duration workload dependent?

MATERIALS AND METHODS

Subjects

A total of 26 subjects participated in the studies. The physical characteristics [gender, age, height, weight, and maximal O_2 consumption ($\dot{V}O_{2\,max}$), when available] of each subject are tabulated in Table 1. Eight of the subjects (6 men and 2 women) tolerated the placement of an esophageal thermocouple probe. Ten male and eight female subjects participated in a short-term study (an acclimation/assessment session followed by sets of paired trials conducted over a

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Table 1. *Gender, age, weight, and $\dot{V}O_{2max}$ of individual subjects*

Subject No.	Gender	Age, yr	Height, cm	Weight, kg	$\dot{V}O_{2max}$, ml $O_2 \cdot min^{-1} \cdot kg^{-1}$
		Single-paired-trial subjects			
3a	M	23	185	91	
3b	F	23	170	55	
3c	M	58	180	80	
3d	M	53	185	109	
3e	M	36	170	89	
3f	M	36	185	76	
3g	M	49	180	69	
3h	F	29	163	63	
3i	F	37	165	71	
3k	M	47	173	69	
3l	M	50	183	84	
3m	M	52	180	97	
3n	F	48	168	60	
3o	M	20	175	73	
3p	F	55	173	55	
3q	F	54	160	64	
3r	F	60	170	64	
		Core temperature effects			
3a	M	23	185	91	
3b	F	23	170	55	
3c	M	58	180	80	
3d	M	53	185	109	
3e	M	36	170	89	
4c	M	20	178	128	
4f	M	20	170	84	
4j	F	20	170	62	
		Multiple-paired-trial subjects			
4a	M	21	179	78	48
4b	M	21	183	85	56
4c	M	20	178	128	37
4d	M	23	183	76	46
4f	M	20	170	84	48
4g	M	21	175	83	53
4h	F	23	155	47	44
4i	M	19	180	69	62
4j	F	20	170	62	44

$\dot{V}O_{2max}$, maximal O_2 consumption. *Subject 4i* participated in only 2 trials/wk.

6-day period). Seven male and two female subjects participated in a long-term study (a 2-wk acclimation and baseline assessment period followed by 8 wk of experimental trials). Informed consent was obtained from each subject using an instrument approved by the Stanford University Institutional Review Board. Each subject was assigned an alphanumeric identifier, which was used thereafter in accordance with Health Insurance Portability and Accountability Act guidelines. Subjects wore their own light exercise clothing and footwear.

Facilities

Trials were conducted on stationary treadmills (model 60, Quinton; model 9800, Nordic Track). $\dot{V}O_{2\,max}$ tests were administered in a 23°C room. The acclimation and heat stress trials were conducted in a 2.44 × 3.35 × 2.44-m (width × length × height) temperature-controlled environmental chamber. The ambient conditions inside the environmental chamber were 40.0 ± 0.5°C. Relative humidity inside the chamber was 20–25% at the start of all exercise trials. However, when evaporative water loss from the subjects exceeded the capacity of the room heating-ventilation-air conditioning system, relative humidity rose as high as 45% by the end of a trial.

Monitoring Equipment

For the $\dot{V}O_{2\,max}$ tests, respiratory gases were measured using a respiratory gases/metabolic analysis system (Parvomedics, Salt Lake City, UT). Heart rate monitors/data loggers (Polar, Kempele, Finland) were used to record and collect heart rate data at 5-s intervals. T_{es} was measured with a Mon-a-therm general-purpose temperature probe (model 503-0028, Mallinckrodt Medical, St. Louis, MO). The probes were self-inserted through the nose or mouth to a depth of 38–39 cm. The probes were connected to a thermocouple transducer/data logger (model OM-4000, Omega Engineering, Stamford, CT), which recorded temperature data at 1-s intervals. Water loss was determined by subtracting postexercise nude weight from preexercise nude weight. Nude weight was determined using a commercially available cargo scale (model c-12, OHAUS) located in a private changing room. At the end of each trial, heart rate and temperature data were downloaded from the data loggers to a central desktop computer and transferred to a spreadsheet (Microsoft Excel) for subsequent offline analysis. Hand-noted data logs were also tabulated for each trial. Subject identifier, date, treatment, pre- and postexercise nude weights, exercise duration, and miscellaneous comments were recorded on the data sheets, along with heart rate measurements, at 3-min intervals.

Heat Extraction Device

The heat extraction device (AVAcore Technologies, Ann Arbor, MI) consisted of a rigid chamber into which a hand could be inserted through an elastic structure that formed a flexible airtight seal around the wrist. The rigid chamber was connected to a pressure sensor, a pressure relief valve (cracking pressure −45 mmHg), and a vacuum source [the building in-house system or a commercially available vacuum pump (1/10th horsepower; model SR-0015-VP, Thomas Industries, Louisville, KY)]. A water trap consisting of a 1,000-ml filter flask (VWR) was plumbed into the vacuum line upstream of the vacuum pump. Activation of the vacuum pump created a slight subatmospheric chamber pressure (−40 mmHg). Inside the chamber, the palm rested on a curved metal surface that was maintained at 22°C or 18°C (±0.5°C) by perfusion of the temperature-controlled water beneath it. The hand interface was tethered via Tygon tubing (8-mm bore, 3-mm wall) to a temperature-controlled heated/refrigerated circulating water bath (model RM 6, Lauda, Konigshofen, Germany) that regulated the temperature of the circulating water. The hand interface device was suspended from the ceiling by an elastic cord so that the subject could maintain normal arm movements while walking.

Experimental Protocols

Pretrial assessments of physical condition. For the $\dot{V}O_{2\,max}$ test, subjects were equipped with the heart rate-monitoring equipment, snorkel mouthpiece, and nose plug from the respiratory gas analysis system. Once equipped, the subjects stood on the idle treadmill for 5 min. After 5 min of baseline data collection, the speed of the treadmill was increased by 3.2 km/h at 3-min intervals until O_2 consumption stabilized for 30 s or until subjective exhaustion. $\dot{V}O_{2\,max}$ and maximum heart rate were noted for each subject.

Baseline assessments of individual physical performance capacities were conducted in the hot room and required that the subjects start walking on a level treadmill at 5.63 km/h for 3 min; then the slope of the treadmill was increased by 2% at 3-min intervals. Elevations of the slope continued until the subject attained a heart rate that was 90% of the estimated age-specific maximum (221 − age) or, if available, the heart rate attained in a prior $\dot{V}O_{2\,max}$ test. The slope of the treadmill in the subsequent experimental trials was initially set at 60–65% of the slope at which the subject reached 90% maximum heart rate in these baseline trials.

Standard daily experimental routines. The subjects arrived at the laboratory 30 min before the start of a trial. Preexercise nude weight was measured, and a heart rate monitor was attached to the subject.

The subjects then rested in a 23°C room for 30 min or until heart rate had stabilized at <70 beats/min. The subjects then moved into the hot room and performed the designated exercise task. Stop criteria for exercise were 90% of maximum heart rate, 120 min of exercise, or subjective exhaustion. On completion of the exercise, the subjects returned to the 23°C room where they sat quietly for 30 min. After the 30-min recovery period, nude body weight was again measured. Before leaving the facility, the subjects consumed a volume of water or a sports drink equivalent in mass to the amount of body weight lost during the exercise trial. All trials for an individual subject were conducted at the same time of day.

Does continuous use of the heat extraction device attenuate core temperature rise during fixed-load exercise? Eight subjects participated in these trials after completing the baseline performance capacity assessment. These trials were part of the larger study on endurance (see *Does use of the heat extraction device improve fixed-load exercise endurance?*), but they included only the subjects who tolerated placement of an esophageal thermocouple probe. The subjects were equipped with a heart rate monitor and esophageal thermocouple probe. The slope of the treadmill for the experimental trials was set at 60–65% of the slope at which the subject reached 90% of his/her estimated maximum heart rate. The trials consisted of the subjects walking on the treadmill at 5.63 km/h at their predetermined slope. Each subject participated in two experimental trials, one with and one without the heat extraction device. The order of the treatments was randomized. The experimental trials were initiated ≥2 days after the acclimation/assessment trial and were separated by ≥2 days.

Does use of the heat extraction device improve fixed-load exercise endurance? Each of the 18 subjects participated in a minimum of three activities: one baseline assessment and two experimental trials. On *day 1*, baseline assessments of individual physical performance capacities were conducted. The slope of the treadmill for the subsequent experimental trials was set at 65% of the slope at which the subject reached 90% of his/her age-adjusted maximum heart rate in the baseline assessment. This workload was selected because it resulted in exercise durations of 20–45 min before the subjects reached the stop criterion (90% of maximum heart rate).

The experimental trials consisted of the subjects walking on the treadmill at 5.63 km/h at their predetermined slope until heart rate reached 90% of the age-adjusted maximum heart rate. The experimental trials were initiated ≥2 days after the acclimation/assessment trial and were separated by ≥2 days. All subjects performed a minimum of two experimental trials: one without the heat extraction device and one with the heat extraction device worn and activated. The order of the treatments was randomized. Six subjects participated in an additional trial to assess the effect of the subatmospheric pressure in the operation of the heat extraction device. For these trials, the heat extraction device was worn and cool water circulated through the device, but the subatmospheric pressure was not applied.

Is the effect of heat extraction on exercise duration workload dependent? To minimize the confound of acclimation in this series of experiments, each subject spent 2 wk acclimating to the experimental environment before participating in 8 wk of experimental trials.

Acclimation to the experimental conditions entailed six 1-h exercise bouts in the hot environment over a 10-day period, during which the subjects walked on a treadmill at 5.63 km/h at a self-selected treadmill slope. Initial $\dot{V}O_{2\,max}$ tests and baseline performance assessments were conducted on each subject 2–4 days after the acclimation period. The $\dot{V}O_{2\,max}$ test and baseline assessments were separated by 24 h. For the baseline physical performance capacity assessment, the stop point was when the subject's heart rate reached 90% of the maximum heart rate that had been attained in the $\dot{V}O_{2\,max}$ trials.

Eight subjects participated in four exercise trials per week: two with and two without cooling treatment. Trial days were Mondays, Tuesdays, Thursdays, and Fridays. The Monday and Tuesday trials and Thursday and Friday trials were paired for treatments, with the treatments ordered randomly. Because of scheduling conflicts, one subject participated in only two trials per week (Thursdays and Fridays). On each day, the subjects walked on a level treadmill at 5.63 km/h for 3 min before the slope of the treadmill was increased to the individual's predetermined slope. The treadmill slope was set for each individual so that his/her 90% maximum heart rate would be reached in a specified exercise period. The individual subjects' slopes were adjusted weekly, but the individual subjects' treadmill slopes remained constant throughout a given week. The targeted exercise duration (time to reach 90% of age-adjusted maximum heart rate) for the control trials was 45–60 min during *weeks 1* and *2*, 35–45 min during *week 3*, 25–35 min during *week 4*, 15–25 min during *week 5*, 10–20 min during *week 6*, 20–30 min during *week 7*, and 35–45 min during *week 8*. The slopes selected for each individual corresponded to ~50–85% of the slopes attained at 90% maximum heart rate in the baseline assessments.

Data Analysis

Endurance times for all trials were tabulated, and raw heart rate and T_{es} data were plotted for each trial using Microsoft Excel software. The raw 5-s interval heart rate data were plotted and screened for artifact and then sorted by 30-s intervals. T_{es} data were treated in a manner similar to the heart rate data. The raw 1-s interval T_{es} data were plotted and screened for artifact and then sorted by 30-s intervals for regression analysis. For display purposes in Fig. 1, these data are plotted in 3-min intervals. Most of these curves were characterized by an initial rapid rise, a break point corresponding to the onset of vasodilation, and a final linear increase (Fig. 1). T_{es} data from the final linear section of each curve were subjected to a regression analysis (available as a graph tool in Microsoft Excel) to determine the best-fit slope of the T_{es} change over time. The rates of T_{es} change data were tabulated and sorted according to individual and treatment and subjected to descriptive statistical analysis and a post hoc paired *t*-test (available as a statistical analysis tool in Microsoft Excel).

For the exercise endurance trials, exercise duration records were verified using the heart rate data. Results from the sets of paired trials were included in subsequent data analysis only if the subject reached the 90% maximum heart rate stop criterion in both of the trials. Exercise durations were sorted by treatments, trial day, and subject, and means ± SE were calculated for each treatment group. All main effects of factors "treatment," "order," "slope," and "subject" were analyzed by one- or two-way ANOVA (Proc GLM in SAS/STAT version 8.02, SAS Institute, Cary, NC), with repeated measures where appropriate. Post hoc paired *t*-tests were used for statistical analysis of the exercise duration results.

RESULTS

Does Continuous Use of the Heat Extraction Device Attenuate Core Temperature Rise During Fixed-Load Exercise?

Cooling treatment attenuated the rate at which T_{es} increased during exercise (Fig. 1). The rise in T_{es} during exercise was characterized by an abrupt linear rise in core temperature early in the exercise bout. At 10–20 min into the exercise bout, a deflection point in the T_{es} vs. time trace could be discerned; then the linear rise in T_{es} continued, but at a lower rate. Cooling had little effect on the rise in T_{es} early in the exercise bouts but substantially attenuated the rise in T_{es} in the later bouts: 2.1 ± 0.4 and 2.8 ± 0.5 (SE)°C/h for cooling and control, respectively ($n = 8$, $P < 0.005$). The attenuation of the late phase of exercise T_{es} rise was consistent in all subjects ($P < 0.005$, paired *t*-test; Fig. 1).

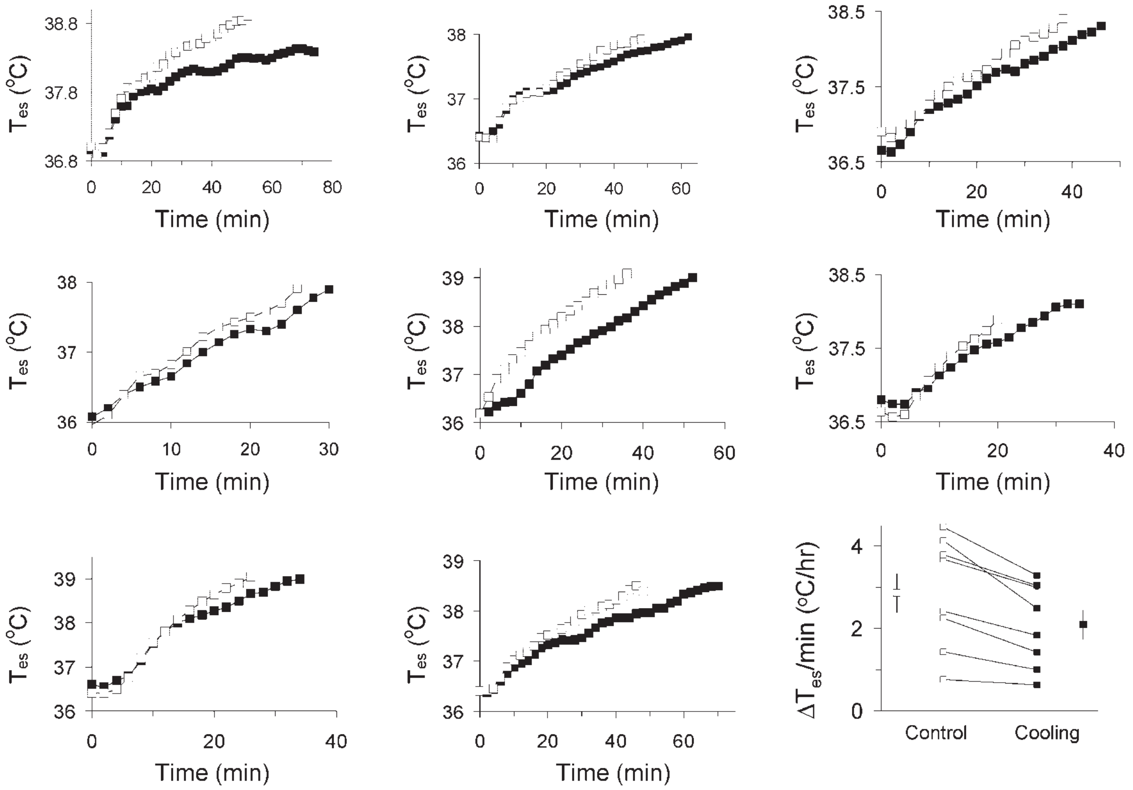

Fig. 1. Effect of heat extraction on rate of esophageal temperature (T_{es}) change during fixed-load exercise in a hot environment. □, Control; ■, heat extraction during exercise. T_{es} vs. time plots are shown for each individual during a control and a cooling trial. In most individual runs, a break point in the curve indicates vasodilation of the hand. Slopes of the curves (ΔT_{es}/min) after these break points were determined by linear regression and are presented at *bottom right*. Symbols for individual subjects are connected by lines. Symbols not connected by lines are treatment group average values (means ± SE, $n = 8$, $P < 0.005$, paired *t*-test).

Does Use of the Heat Extraction Device Improve Fixed-Load Exercise Endurance?

Cardiovascular drift was observed in all trials. All subjects ($n = 18$) reached the 90% maximum heart rate stop criterion. The effects of treatment on the rate of cardiac drift were similar to the effect on T_{es} rise (Fig. 2). According to reports from the subjects, the 90% maximum heart rate provided a useful index for impending subjective exhaustion. The combined application of cooling and subatmospheric pressure increased exercise duration by 43%: 46.1 ± 3.4 and 32.3 ± 1.7 (SE) min for cooling and control, respectively ($n = 18$; Fig. 3*A*). A post hoc *t*-test established that there was a significant effect of treatment on exercise duration ($P < 0.001$).

Six subjects completed the trials under three experimental conditions: control (no treatment), cooling only, and cooling and subatmospheric pressure (Fig. 3*B*). In this subset of subjects, cooling only (i.e., placing a hand in the heat extraction device with cooling fluid circulating but without application of subatmospheric pressure) provided little performance benefit (34.1 ± 3.0 and 38.0 ± 3.5 min for control and cooling only, respectively), but the combination of cooling and subatmospheric pressure provided a substantial increase in endurance (57.0 ± 6.4 min, $n = 6$; Fig. 3*B*). ANOVA revealed a significant effect of the factor treatment among groups ($P < 0.01$, 1-way ANOVA). Post hoc *t*-tests established that treatment with the fully activated device (i.e., cooling and subatmospheric pressure) resulted in a significant improvement in

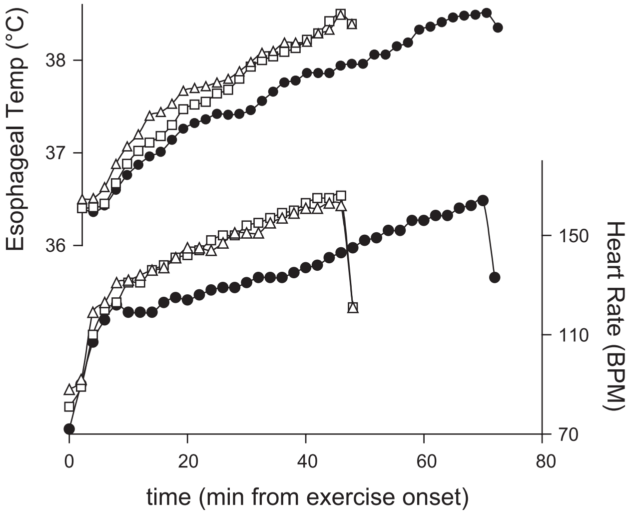

Fig. 2. Combined application of subatmospheric pressure and a cool thermal load to a single hand attenuates rise in T_{es} and cardiovascular drift during fixed-load exercise in a hot environment in a single subject. Subject walked at 5.63 km/h up a 9% slope on a treadmill in a hot environment (40 ± 1°C, 35–45% relative humidity). □, No treatment; ●, 1 hand placed in the heat extraction device in which water was circulating and a pressure differential was maintained; △, 1 hand placed in the heat extraction device in which water was circulating but no pressure differential was maintained. Stop criterion for these trials was 90% of the subject's age-adjusted maximum heart rate (i.e., 163 beats/min). An abrupt drop in heart rate occurred at the end of exercise. Effective heat extraction treatment extended exercise duration. BPM, beats/min.

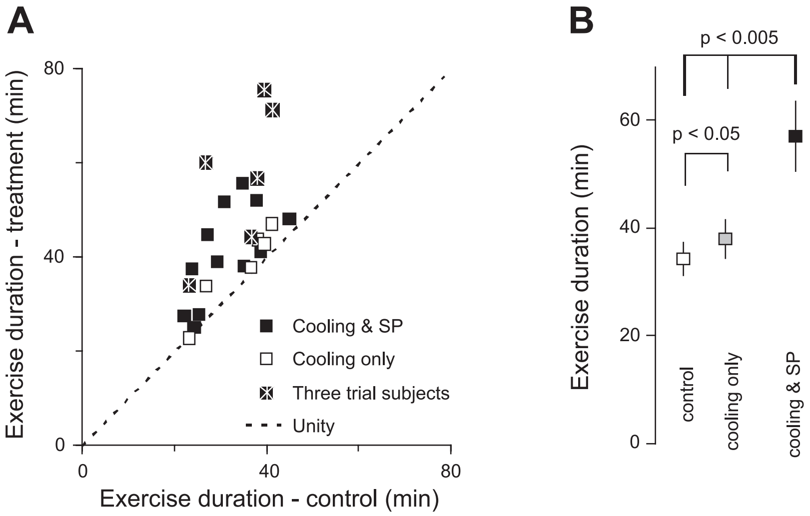

Fig. 3. Effects of cooling with and without subatmospheric pressure (SP) on exercise duration in a hot environment. Eighteen subjects participated in cooling and control trials. A subset of that group ($n = 6$) participated in an additional trial with cooling only. *A*: exercise duration with treatment vs. exercise duration in control condition shown as individual data points. Three-trial subjects participated in control, cooling only, and combined cooling and subatmospheric pressure tests. Heat extraction had a significant effect on exercise duration ($P < 0.005$, post hoc *t*-test). *B*: group data from the 6 subjects who participated in 3 trials. Values are means ± SE. Combined cooling and subatmospheric pressure treatment resulted in a significant improvement in performance over the other treatments ($P < 0.005$, post hoc *t*-test). Results from cooling only were marginally different from control ($P < 0.05$).

performance over the other treatments (cooling only or control; $P < 0.005$).

Is the Effect of Heat Extraction on Exercise Duration Workload Dependent?

The combined application of cooling and subatmospheric pressure to one hand increased exercise duration at all workloads (Table 2). ANOVA revealed significant effects of the factors treatment and treadmill slope ($P < 0.0001$ for both factors, 2-way ANOVA). The effect of treatment (cooling) was affected by the slope at which the exercise was performed [significant interaction between the main factors ($P < 0.025$)].

The exercise duration data from the entire set of paired trials were grouped according to treatment and analyzed ($n = 96$). Mean exercise duration with cooling was 48.0 ± 2.9 min compared with 30.7 ± 1.5 min without treatment: a mean increase of 56% ($P < 2.0 \times 10^{-13}$, 2-tailed paired *t*-test). The magnitude of the cooling treatment effect was correlated with endurance duration during the control condition (Fig. 4). This relation appeared to be exponential. Seventy percent of the variance in the improvement with the cooling treatment could be accounted for by an exponential function fitted to the data: $y = 12.724e^{0.0372x}$, where y and x represent exercise duration with and without treatment, respectively.

Table 2. *Weekly summaries for multiple-paired-trial study*

Week No.	*n*	Slope	No. of Paired Trials	Exercise Duration, min		Ratio
				Cooling	Control	
1	9	9.6±1.0	13[a]	76.6±8.0	48.7±3.7	1.57
2	9	9.6±1.0	6[b]	77.5±11.0	50.4±4.8	1.54
3	9	12.3±1.4	14[c]	71.8±7.8	41.8±3.5	1.72
4	9	13.8±1.3	15	41.3±7.4	28.3±4.7	1.46
5	9	14.9±1.4	17	26.6±3.9	18.9±1.4	1.41
6	6[d]	16.6±1.9	11	23.8±1.4	17.2±2.0	1.39
7	6	15.5±2.4	11	32.0±5.8	24.7±5.0	1.30
8	5	12.3±2.4	8[e]	65.0±6.6	37.4±2.2	1.74

Values are mean ± SE; *n,* number of subjects. Paired trials represents pairs of trials in which subjects reached 90% maximum heart rate stop criterion in both trials; only data from paired trials in which individual subjects completed experimental and control runs were included. Reasons for not completing trials were exceeding 120 min of exercise, blisters, illness, and travel-related absences. Ratio represents ratio of mean exercise duration with heat extraction to mean exercise duration without heat extraction. [a]Four cooling trials were terminated at 120 min. [b]Six cooling trials were terminated at 120 min; 5 trials were cancelled because of subject illness. [c]One trial was terminated at 120 min, 3 were cancelled because of illness. [d]Three subjects quit the study because of prior commitments. [e]One trial was terminated at 120 min.

DISCUSSION

Common experience along with scientific studies in animals and humans support the generalization that the ability to sustain a high level of aerobic exercise is limited by core body temperature and, therefore, indirectly, by high ambient temperature (7, 18, 23). The corollary to that generalization is that extraction of heat from the body core should increase the capacity to sustain aerobic exercise. Studies using various methods to achieve reductions in body heat content before exercise onset (precooling) demonstrated that aerobic endurance can be extended by these maneuvers, probably because of

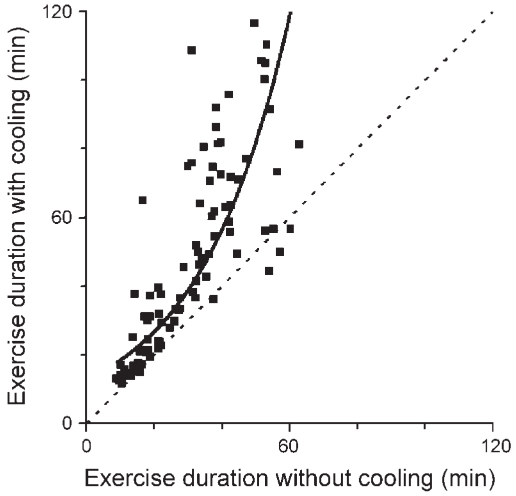

Fig. 4. Effect of cooling on exercise duration: a comparison of 96 paired treatment trials. Effect of cooling was affected by exercise duration during the control condition: the longer the duration of exercise in the control condition, the greater the cooling treatment effect. An exponential function ($y = 12.724e^{0.0372x}$, where y and x represent exercise duration with and without treatment, respectively) accounted for 70% of the variance in the data.

creation of a greater sink for metabolic heat generated during the exercise (see Ref. 16 for review). A recent study by Wilson et al. (24) is an excellent example. Precooling was achieved by immersion of the subjects up to the suprailiac crest in cool (17.7°C) water for 30 min before exercise on a fixed bicycle at 60% $\dot{V}O_{2\,max}$ (24). The precooling created a negative heat load on the body; as a result, the subjects experienced a doubling of the exercise duration required to raise their body temperatures 0.5°C. Clearly, decreasing the rate of rise in body heat content during exercise improves endurance.

Precooling techniques, however, have limitations. They can require cumbersome equipment and significant time of application just before exercise, e.g., 30 min in the study of Wilson et al. (24). In addition, they have a finite benefit that is determined by the amount of negative heat storage that is possible and the rate of positive heat storage during exercise. Thus they are optimally useful in events lasting <1 h. A method that would enable repeated or continuous heat extraction during exercise would be of even greater benefit than precooling in extending aerobic endurance and protecting against heat stress.

Here we show that continuous extraction of heat from the body through only one hand during exercise can increase aerobic endurance by a large percentage. How is such a large increase in physical performance possible from the cooling of such a small area of the body surface? The answer resides in the fact that the palms of the hands, the soles of the feet, and some areas of the face in humans have circulatory adaptations for the dissipation of metabolic heat. These adaptations consist of AVAs that can shunt blood directly from arterioles to venous plexuses, which act as radiators (3, 8, 9). The blood cooled in such a venous plexus returns directly to the core of the body. The heat extraction device we used in these studies has the ability to enhance the heat exchange capacity of those radiators by distending the venous plexus vessels through the application of subatmospheric pressure. Furthermore, reflex vasoconstriction of the AVAs is prevented by maintenance of a heat-sink temperature above the threshold for local vasoconstriction.

Under the conditions of these studies, application of subatmospheric pressure to the hand was critical for enhancing heat transfer. Figure 2 is an example of the effect of heat extraction using the device with and without application of subatmospheric pressure. Three trials at the same workload and ambient conditions are shown. The heart rate curves determined the end of exercise, and, in this example, >60% more time was required to reach that criterion when the heat extraction device was used. When the device was used to cool without application of subatmospheric pressure, there was, at best, a limited beneficial effect. The results seem in direct conflict with those of Selkirk et al. (22), who reported that 20 min of submersion of both hands and arms up to the elbows in turbulently mixed 17°C water during intermissions between 1-h exercise bouts by firefighters clad in full turnout gear provided a substantial physical performance benefit (an ~32% improvement in endurance time). There were considerable methodological differences between that study and ours, the largest (aside from the cooling techniques themselves) being the attire of the subjects, the exercise regimens, and the timing of cooling. In our studies, the subjects were clad in warm-weather exercise garb and were continuously cooled throughout a single sustained exercise bout. In the study of Selkirk et al., the subjects wore heavy insulation layers during exercise-rest cycles (some of the insulation layers were removed during the resting phases of the cycles) and received cooling treatment only during some of the resting phases. Despite the methodological differences, both studies demonstrate substantial benefits from local cooling under specific thermally stressful conditions. It is likely that much of the cooling effect of forearm immersion reported by Selkirk et al., Allsopp and Poole (2), and others is mediated through the thermoregulatory vasculature in the hands.

In the studies reported here, we used heart rate as the determining factor for marking maximum exercise duration. Alternative metrics for comparing exercise duration could have been T_{es} or the point of perceived exhaustion. In preliminary work not reported here, we routinely saw a good correlation between perceived exhaustion and T_{es}, consistent with the study of Gonzalez-Alonso et al. (7), in which the initial core temperatures of subjects were manipulated by precooling or preheating just before exercise in a hot environment (40°C) at 60% $\dot{V}O_{2\,max}$ until volitional exhaustion. The main conclusion of that study was that exhaustion occurred at the same high core temperature regardless of the starting conditions. Another result from that study was that, after 10 min of exercise, changes in heart rate were closely related to changes in T_{es} regardless of the starting conditions. Given these results and the difficulty many subjects have with esophageal thermocouples, we decided that heart rate was the best objective metric for our comparisons of endurance.

One would expect that the ability of the heat extraction device to increase endurance would depend on the intensity of the exercise. If the AVAs are fully open and the parameters of the heat extraction device are held constant, there should be a maximum attainable level of heat extraction. Therefore, as workload increases, that maximum level of heat extraction should be a lesser and lesser proportion of the total heat produced. As a result, core body temperature should rise faster the higher the workload, even with the heat extraction device. This expectation is fulfilled in the results shown in Table 2 and Fig. 4. The intensity of the workload was altered by changing the slope of the treadmill. At the initial slope of 9.3%, the cooling trials were 50–70% longer than the control trials, but at the highest workloads the difference dropped to 30–40%. The effect of cooling on exercise endurance appears to be exponentially related to workload (Fig. 4).

More work is required to fully characterize the effectiveness of the heat extraction device in extracting heat from the body core, but the data obtained so far indicate that this technology has great potential for extending endurance of individuals working in hot environments. The results of this study are of interest not just to those who want to improve athletic performance but also to those in professions that require high levels of physical work in thermally stressful environments. This would include military personnel, firefighters, construction workers, and a variety of industrial workers. Extracting heat from the body core is of value in protecting such individuals from heat stress and may facilitate recovery from episodes of hyperthermia.

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DISCLOSURES

Patents have been issued for the technology described in this manuscript [D. Grahn and H. C. Heller (Inventors), Stanford University (Assignee)], and Stanford University has entered into a licensing agreement with AVAcore Technologies, Inc., for the commercialization of the technology. Included in the license is a royalty agreement that grants Stanford University a percentage of the net sales of the technology, which will be shared by the University and the inventors. D. Grahn and H. C. Heller are founders of AVAcore Technologies but receive no ongoing compensation from the company.

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