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ORIGINAL ARTICLE

Palm cooling to reduce heat strain in subjects during simulated armoured vehicle transport

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Abstract This study examined whether palm cooling (PC) could reduce heat strain, measured through changes in core, mean skin, mean body temperatures, and thermal sensation in resting hyperthermic subjects wearing chemical protective garments. Ten male subjects performed three exercise bouts (6.1 km h^{-1}, 2–4% grade) in a hot, dry environment [mean (SD) air temperature 42.2 (0.5°C), relative humidity 36.5 (1%)] until core temperature reached 38.8°C. Subjects then simulated transport in an armoured vehicle by resting in a seated position for 50 min with either no cooling (NC), (PC at 10°C) or palm cooling with vacuum application around the hand (PCVAC, 10°C, 7.47 kPa negative pressure). Core, skin, and mean body temperatures with PC and PCVAC were lower ($P < 0.05$) than NC from 15 to 50 min of cooling, and thermal sensation was lower ($P < 0.05$) from 30 to 50 min, with no differences in any variables between PC and PCVAC. Maximal heat extraction averaged 42 (12 W), and core temperature was reduced by 0.38 (0.21°C) after 50 min of PC. Heat extraction with PC was modest compared to other cooling approaches in the literature.

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Introduction

During desert operations, it has been reported that the interior of armoured vehicles reach temperatures as high as 54.5°C (personal communication: Tom Lovell, Foster-Miller Inc, Waltham, MA, USA). Confounding the situation, soldiers inside these vehicles are dressed in battle dress uniform, helmets, and body armour, which cover much of the surface area available for heat exchange. At intervals, the soldier must rapidly exit the vehicle to respond to fire or to perform foot patrols. During these patrols, the protective gear increases metabolic rate when moving and decreases heat dissipation, resulting in significant heat storage (Dorman and Havenith 2009).

Under such extreme heat stress conditions, the risk of heat illness is great and the ability to remain alert and react quickly may be impaired (Racinais et al. 2008). Therefore, cooling could improve performance and reduce heat casualties. Two methods previously shown effective in cooling hyperthermic soldiers are hand immersion (House et al. 1997, 2003) and liquid cooling garments (LCG) (Cadarette et al. 2006; Cheuvront et al. 2003). However, both methods have disadvantages to use during armoured vehicle transport. Hand immersion produces the logistical problem of incorporating open water reservoirs inside a vehicle that must travel over treacherous terrain. LCG require a tethered system to be operational, and must be worn under the body armour to be effective (Cheuvront et al. 2003). Because of electrical and fluid connectivity requirements, the LCG must be removed before exiting the vehicle, as it would impede heat loss during patrols by increasing load and heat production. Unfortunately, removing the LCG requires removal of body armour, leaving the soldier vulnerable to attack.

Clearly, the operational shortcomings of these cooling methods convey the possibility that a better modality may exist to cool hyperthermic soldiers during armoured vehicle transport. The best choice for a cooling device would be small, require minimal power, and be immediately detachable when the soldier was required to exit the vehicle. One potential commercial cooling device is the Rapid Thermal Exchanger (RTX) (Avacore Inc. Ann Arbor, MI, USA). Using this device, the palm is rested on a cooling plate while the whole hand is enclosed in an elastomer shell while negative pressure is applied around the hand. The palm of the hand is proposed as an efficient site for heat exchange because it has a high surface area to mass ratio and contains many arteriovenous anastomoses and venous plexuses (Johnson et al. 1995), allowing direct delivery of cooled blood from the periphery to the core (Tipton et al. 1993). The local vacuum is proposed to help prevent vasoconstriction of the palm capillaries during cold exposure, as this would interfere with heat extraction from the hand (Grahn et al. 2005).

Hand cooling through water immersion has been shown effective in hyperthermic firefighters (Selkirk et al. 2004) and naval recruits (House et al. 2003). It has even been recommended as the "cooling method of choice" for the British Royal Navy (House et al. 1997). However, providing an open, chilled water bath for cooling in a moving operational vehicle may be problematic. The RTX requires the palm to remain in contact with a cooling plate, but detachment is simply performed by removing the hand. RTX developers envision that cooling plates could be mounted near the seats of an armoured vehicle for easy access. It is unclear whether the vacuum application would be needed in subjects already heated, as previous studies have shown that once core temperature is elevated, hand vasoconstriction no longer occurs (House et al. 2003; Livingstone et al. 1995). It also is unclear whether palm cooling (PC) could remove enough heat from the body to provide sufficient cooling under severe heat stress conditions.

The primary purpose of this study was to investigate whether PC reduces measures of thermal strain (T_{es}, T_{sk}, HR, thermal and comfort sensations) in hyperthermic subjects simulating armoured vehicle transport, measured through changes in body temperatures and thermal/comfort sensation. A secondary purpose was to determine whether the addition of negative pressure around the hand during palm cooling (PCVAC) would result in greater heat extraction and further reduction of thermal strain compared to PC alone. We hypothesized that thermal strain would be lower with PC compared to rest without cooling, and that the addition of negative pressure would provide no additional cooling effects.

Methods

Subjects

Ten subjects completed this study. Subject descriptives, presented as mean (SD), were as follows: height 179 (5 cm), weight 74.8 (12.4 kg), age 24.1 (5.7 years), body fat 9.0 (7.2%), and peak oxygen uptake (VO_2pk) 57.3 ml kg^{-1} min^{-1}(10.1 ml kg^{-1} min^{-1}). Subjects were selected to have characteristics similar to Army recruits and to have low cardiovascular disease risk (less than 2 coronary artery disease risk factors; Armstrong et al. 2006). The protocol for this study was approved by the US Army and University of New Mexico Institutional Review Boards, and was performed in accordance with the ethical standards of the 1964 Declaration of Helsinki. All subjects provided informed, written consent prior to participation.

Preliminary testing

Each subject performed a continuous graded treadmill test in a temperate room (22–24°C dry bulb temperature, 30–40% RH) to determine VO_2pk through open circuit spirometry. VO_2pk was defined as the highest 30-s value when two of the following criteria were met: (a) a plateau (change in $VO_2 < 150$ ml min^{-1}) with increase in workload, (b) a maximal respiratory exchange ratio greater than 1.1, and (c) heart rate (HR) greater than 95% of the age-predicted maximum (220 − age). Percent body fat was determined by measuring three skinfold sites (chest, abdomen, thigh) in triplicate (Lange, Beta Technology, Santa Cruz, CA, USA). Population-specific equations were used to determine body density and body fat percentage (Jackson and Pollock 1978).

Experimental design

Ten subjects performed four heat stress trials. The first trial was always a no cool familiarization session (FAM) to avoid learning effects. After this trial, the three study conditions; no cool (NC), palm cooling without negative pressure (PC), and PC with negative pressure (PCVAC) were performed in a counterbalanced order. All heat stress trials were separated by a minimum of 5 days to minimize carryover effects. All trials for a given subject began at the same time of day to avoid diurnal variation.

Experimental protocol

To avoid external confounding variables, subjects were instructed to consume carbohydrate rich meals for the 24 h prior to each experiment, and to drink an extra 500 mL of fluid the night before each experimental condition. When subjects arrived at the lab, nude body weight within 0.1 kg (Seca Scale, Birmingham, UK) and urine osmolality (Advanced Osmometer, Model 303, Advanced Instruments Inc, Norwood, MA, USA) were measured. Subjects were considered hydrated and continued with the experimental protocol if their urine osmolality was $\leq$600 mosm kg^{-1}.

Uncovered skin thermistors (Grant Instruments Ltd, Cambridge, UK) were then attached to the upper arm, upper thigh, chest, and calf with elastic straps. A calibrated oesophageal thermistor (T_{es}) (YSI Precision 4400 Series, Yellow Springs Inc., Yellow Springs, OH, USA) was inserted to a depth approximately one fourth of subject height (depth was adjusted ±2.54 cm to attain the highest reading). Thermistors were connected to a data logger (Grant Instruments Ltd, Cambridge, UK), which recorded T_{es} and skin temperatures (T_{sk}) every 5 s throughout the trial. From these skin thermistors, mean skin temperature was calculated as (Ramanathan 1964):

$$(T_{sk}) = 0.3(T_{chest}) + 0.3(T_{arm}) + 0.2(T_{thigh}) + 0.2(T_{calf})$$

After the thermistors had been attached subjects donned military clothing, including a t-shirt, battle dress uniform (BDU, St. Louis, MO, USA), and a chemical protective suit (Coleman's Surplus, Item 010101-1, Millersburg, PA, USA). Subjects also wore neoprene gloves to prevent heat exchange from the hands. This clothing configuration is mission oriented protective posture (MOPP) 4, with a reported clo (insulation) factor of 1.5 (Montain et al. 1994). Once clothed, subjects entered the environmental chamber which was controlled at 42.2 (0.5°C), 37 (1%) RH. A heat stress monitor (Metrosonics hs-3600, Oconomowoc, WI, USA) was used to collect ambient data (dry bulb, wet bulb, wet bulb globe temperature, and RH) at 5-min intervals throughout the trial.

Subjects stood quietly for 5 min while initial readings of HR, T_{es}, T_{sk}, comfort, and thermal sensation scores were obtained. The comfort sensation scale ranged from 1 to 5 for comfort, with 1 = comfortable, and 5 = intolerable. The thermal sensation scale ranged from 1 to 8, with 1 = cold, and 8 = unbearably hot. These sensation scales were modified from their original format (Gagge et al. 1967). After this preliminary data had been gathered, subjects walked at 6.1 km h^{-1} (3.8 mph), 2–4% grade until T_{es} reached 38.8°C. To assess whether exercise heat stress was equivalent among the three experimental conditions, subjects' scores on the physiological strain index (PSI) were calculated at 5-min intervals during exercise as (Moran et al. 1998):

$$\mathrm{PSI} = 5({}_cT_{es} - {}_iT_{es})(39.5 - {}_iT_{es})^{-1} + 5({}_c\mathrm{HR} - {}_i\mathrm{HR})(180 - {}_i\mathrm{HR})^{-1}$$

where ${}_cT_{es}$ = current core temperature, ${}_iT_{es}$ = core temperature at exercise onset, ${}_c$HR = current heart rate, and ${}_i$HR = heart rate at exercise onset.

In the 3-min interval following the end of exercise and the start of the simulated armoured vehicle transport, subjects moved from the treadmill to a semi-recumbent chair, positioned a balaclava over the head, had foot coverings put around the shoes, and laser doppler probes (Perimed, Model PF5010 LDPM, Jarfalla, Sweden) attached to the nail bed of the ring finger for measurement of nailbed blood flow (NBF) in arbitrary perfusion units (PU), allowing assessment of vasoconstriction. NBF values were normalized (nNBF) by calculating a percentage change for each time point from the time when the subject's hand first contacted the RTX cooling plate. nNBF was calculated as:

$$n\mathrm{NBF} = {}_y\mathrm{NBF}/{}_x\mathrm{NBF}$$

where ${}_x$NBF represents NBF at initial cooling plate contact, and ${}_y$NBF represents NBF at time point of interest.

NBF was used to represent blood flow to the palm because both sites contain glabrous skin, which lacks active vasodilator capacity (Yamazaki and Sone 2006). Palm blood flow was not measured directly because this would have impeded palm contact with the cooling plate. Once the laser doppler probe was attached subjects sat for 50 min to simulate armoured vehicle transport, during which time either NC, PC or PCVAC was applied. The RTX used in this study was the "dome version", originally designed by AVAcore technology Inc. (Ann Arbor, MI, USA), remodeled by Wells Machinery (Athens, AL, USA). This version of the RTX has a Plexiglas shell (covered with rubber) that encloses the entire hand at the wrist and an aluminum plate contoured for hand contact. An elastomer sleeve was secured around the wrist at the level of the styloid process, producing a seal between the RTX and the wrist that allowed negative pressure to be maintained around the hand. Chilled water circulated through tubing which cooled the aluminum plate. Water flow rate (ALICAT scientific flow transducer, ALICAT Scientific, Tucson, AZ, USA) was controlled at 2.5 L min^{-1}, and negative pressure was controlled at −7.47 kPa for an 8 s on, 3 s off cycle by an integrative cart (CSA engineering, Mountain View, CA, USA) run with customized Lab View software (LabVIEW, National Instruments, Austin, TX, USA). RTX input/output temperatures (Automatic Systems Laboratory precision thermometer, model F200, Surrey, UK) were monitored, with input temperature set at 10°C. Background heat extraction was determined as the average heat extraction measured during the 15 min before and after each trial involving cooling. Net heat extraction was calculated through direct calorimetry as:

$$Q(\text{watts}) = (C\rho V(\Delta T)) - (B_1 + B_2/2),$$

where Q represents the heat transfer rate, C is the specific heat of water, ρ is the density of water, V is the volume flow rate of water through the device, ΔT is the difference in water temperature across the heat exchanger (outlet temperature minus inlet temperature), B_1 is background heat extraction for the 15 min preceding RTX application, and B_2 is the background heat extraction for the 15 min following RTX application.

At the conclusion of each trial, with the subject still seated in the environmental chamber, occlusion at the brachial artery was performed by inflating an arm cuff to 240 mmHg. Arm occlusion was held for 1 min and then released, with subjects sitting for an additional minute without occlusion. This occlusion/release technique was used to provide a relative indication of the PU value at severe vasoconstriction, as a relative indication of whether the hand was vasoconstricted during the test due to contact with the cooling plate.

Statistical analyses

Power analysis

The sample size necessary to show a statistical difference was calculated from the mean and SDs of a previously reported hand cooling study (House et al. 1997). Using a commercially available program (Statistica version 7.1, Statsoft Inc, Tulsa, OK, USA), a total of nine subjects was found sufficient to provide adequate statistical power ($\alpha = 0.05$, $\beta = 0.9$).

Statistical design

Urine osmolality and exercise heat storage were examined with one-factor ANOVAs with repeated measures design. T_{es}, T_{sk}, HR, thermal sensation, comfort sensation, and NBF during the simulated armoured vehicle transport were examined with a two-factor ANOVA, with intervention (NC, PC, or PCVAC) and armoured vehicle transport simulation time (0–50 min) as the repeated measures factor. Heat extraction (W) between PC and PCVAC was also compared with a two-factor ANOVA, with intervention (PC and PCVAC) and armoured vehicle transport simulation time (0–50 min) as the repeated measures factors. The effect of cooling time on heat extraction was analysed with a simple regression for each of PC and PCVAC. Significant main effects were further compared with Tukey's honestly significant difference post hoc tests. For all analyses, significance was set at $P \leq 0.05$. All data are presented as the mean (SD).

Results

Exercise heating period

Subjects' urine osmolality upon reporting to the laboratory was 208 (156 mOsm/kg), indicating all trials began in a euhydrated state. They required 33.8 (9.5 min) of walking to increase their oesophageal temperature to 38.8°C. The average score on the physiological strain index over the final 5 min of exercise was 7.59 (1.07), which equates to high heat strain. There were no differences ($P > 0.05$) in urine osmolality, exercise duration, or the physiological strain index between conditions.

Resting cooling period

One NC trial was terminated after 41 min of rest due to subject request. The remaining nine subjects completed 50 min of rest in the NC trials. All subjects completed 50 min of rest in both the PC and PCVAC trials. To retain equal subject comparisons across conditions an n of 10 was used for statistical evaluations through 40 min of simulated vehicle transport, and an n of 9 was used for the remaining 10 min.

Compared to NC, PC, and PCVAC significantly reduced T_{es} and T_{sk} ($P < 0.05$) from 15 through 50 min of simulated armoured vehicle transport, and thermal sensation from 30 through 50 min (Fig. 1). Neither PC nor PCVAC reduced HR over NC ($P < 0.05$). There was a significant ($P < 0.05$) condition by time interaction for comfort rating, where discomfort increased during NC from 15 to 45 min of rest, then decreased to a value similar to PC and PCVAC at 50 min. Table 1 reports values for HR, T_{es}, T_{sk}, comfort, and thermal sensation after 50 min of simulated armoured vehicle transport. A significant inverse relationship was found between cooling time and heat extraction, where heat extraction decreased as cooling time increased in both PC ($r^2 = 0.83$, $P < 0.05$) and PCVAC ($r^2 = 0.86$, $P < 0.05$) trials (Fig. 2). No differences ($P > 0.05$) were seen in any of the measured variables between PC and PCVAC.

Multiple approaches were used to assess whether palm blood flow was constricted with cooling and whether vacuum application was able to offset constriction if it occurred. Absolute NBF and nNBF values presented similar patterns of response, with neither being increased ($P > 0.05$) with PCVAC compared to PC. Occlusion of the

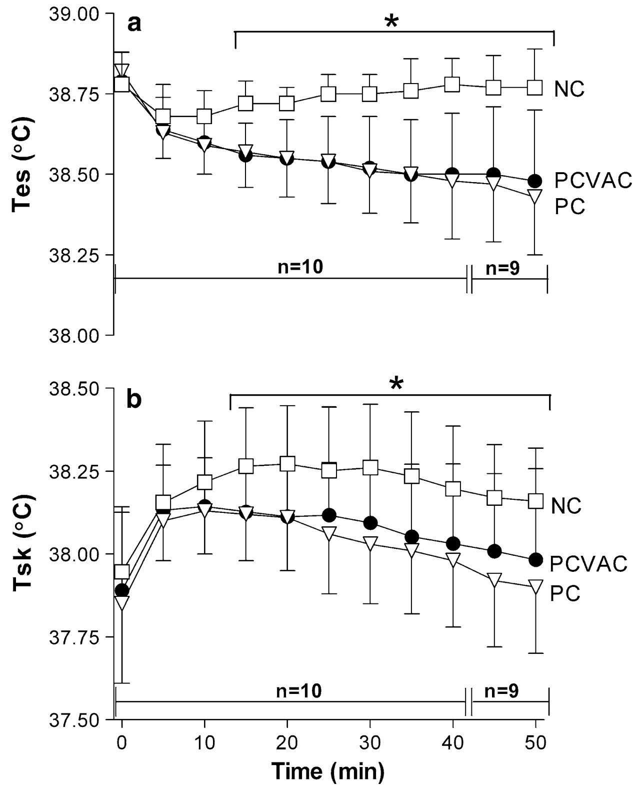

Fig. 1 **a** Core temperature (T_{es}) and **b** mean skin temperature (T_{sk}) during 50 min of simulated armoured vehicle transport with no cool (NC), palm cooling (PC) and palm cooling with vacuum (PCVAC). *Asterisk* indicates that PC and PCVAC are different than NC at the time points indicated, $P \leq 0.05$. Data shown are the mean (SD), $n = 10$ for 0 through 40 min, and 9 for 41 through 50 min

brachial artery with a cuff pressurized to 240 mmHg resulted in a significant ($P < 0.05$) decrease in NBF in all experimental conditions. NBF immediately rebounded upon occlusion removal (Fig. 3).

Discussion

A significant concern during military operations in hot environments is the prevention of heat stress in soldiers who must wear protective garments and be transported in armoured vehicles. Often these vehicles do not contain climate control because of power or noise limitations, or because of concern about susceptibility to chemical warfare if outside air were circulated in the vehicle. Anecdotally, temperatures as high as 50°C have been reported in such vehicles. In this paper, we evaluated a novel personal cooling approach that may have application for this situation. We observed significantly lower T_{es}, T_{sk}, and thermal sensation when using PC compared to NC.

However, the amount of cooling with or without vacuum was small. It averaged only 42 (12 W), resulting in a core temperature decrease of 0.35 (0.21°C) over the 50 min cooling period. In comparison, in a study with subjects and climactic conditions similar to our own, cold water immersion (10°C) of both hands to the wrist for 20 min produced a heat extraction ~334 W, and a reduction in core temperature of 1.6°C (House et al. 1997). The higher cooling capacity reported by House et al. (1997) is likely due to the fivefold greater specific heat capacity of water over aluminum, as well as to the greater surface area available for heat exchange. It should also be noted that insulated auditory canal temperature was used in the House study, which may also have influenced results. The cooling capacity of LCG, which ranges from 500 to 600 W when worn under protective garments (Flouris and Cheung, 2006), is also much higher than PC. Thus, while PC is easier to apply than other cooling modalities, it has a limited capacity for heat extraction.

While PC's low cooling capacity is clearly a limitation, it should be noted that it may be capable of delaying the onset of heat stress during armoured vehicle transport. To illustrate this point, we have regressed core temperature responses in the NC condition to determine how much longer subjects could have sat before reaching critical heat stress (defined by our group as a core temperature of 39°C). We removed the first 5 min of resting data to correct for the initial core temperature drop resulting from transition from exercise to seated rest. NC subjects would have attained 39°C if they had sat for an additional 30 min. In contrast, core temperature was falling in both cooling conditions, predicting subjects would have attained core temperatures of 38.04 and 38.15°C in the PC and PCVAC conditions at this same time point. Regression coefficients for the core temperature slopes were 0.87, 0.98, and 0.91 for the NC, PC, and PCVAC conditions, respectively.

Table 1 Thermoregulatory strain variables: values after 50 min of simulated armoured vehicle transport

Condition	Heart rate (bpm)	Core temperature (°C)	Skin temperature (°C)	Comfort sensation (1–5)	Thermal sensation (1–8)
NC	115 (12)	38.77 (0.11)	38.14 (0.17)	3.0 (0.9)	6.4 (1.2)
PC	118 (13)	38.43 (0.18)*	37.90 (0.20)*	2.4 (1.3)	5.1 (1.4)*
PCVAC	120 (15)	38.48 (0.22)*	37.98 (0.27)*	2.3 (1.3)	5.4 (1.0)*

* Different from NC condition; $P < 0.05$

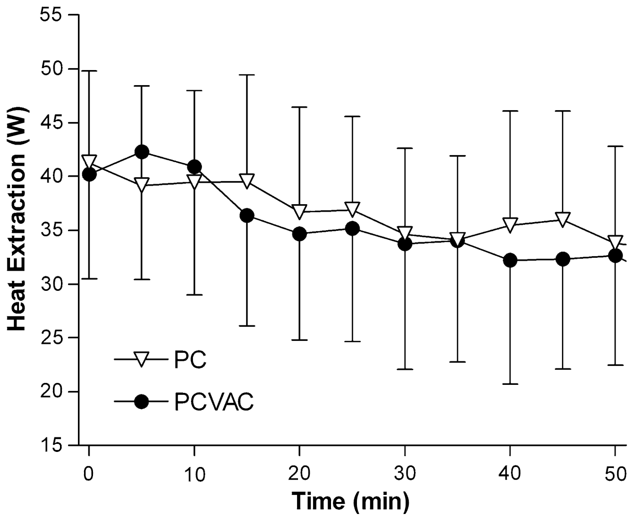

Fig. 2 Watts (W) of heat extraction with PC and PCVAC during 50 min of simulated armoured vehicle transport. Heat extraction between conditions was not different. Data shown are the mean (SD), $n = 10$

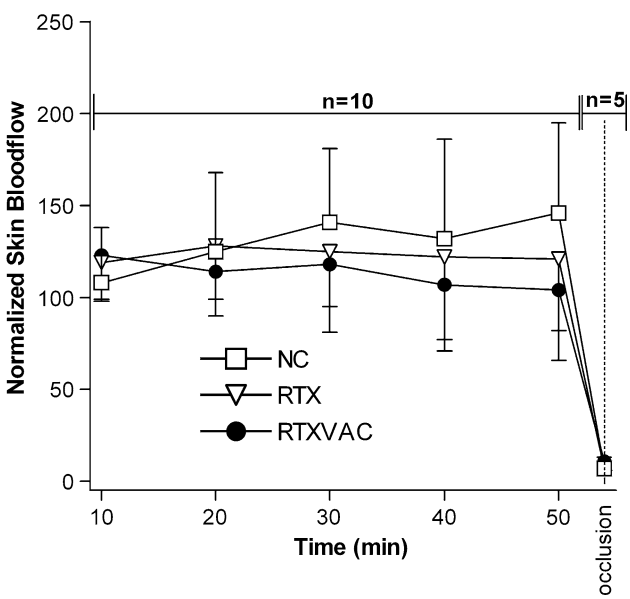

Fig. 3 Nailbed bloodflow (NBF) during 50 min of simulated armoured vehicle transport with no cool (NC), PC, and PCVAC application, normalized to the onset of cooling. Data shown are the mean (SD). For the 50 min of cooling application $n = 10$, while during the 1 min of venous occlusion (produced by inflating a cuff to 240 mmHg at the brachial artery) $n = 5$

Effect of vacuum during palm cooling

We hypothesized that applying vacuum during cooling would not increase hand skin blood flow. This may be explained by observations from previous studies which used cold water immersion; when subjects already are hyperthermic when cooling was applied, immersion of the hands, arms, or feet in 10°C water does not likely produce vasoconstriction (House et al. 1997, 2003; Livingstone et al. 1995). Testing of this hypothesis was important, as it has previously been reported by the developers of the RTX (the same palm cooling device tested here) that palm cooling without negative pressure provided little benefit to subjects during treadmill running, while palm cooling with negative pressure slowed the rate of rise in core temperature and increased running endurance (Grahn et al. 2005).

We examined several indicators to confirm whether vasoconstriction was occurring in our study. Inspection of our NBF records during intermittent vacuum application showed no fluctuations in NBF as the vacuum oscillated on and off. In addition, heat extraction and thermal responses were similar during PC and PCVAC trials, suggesting that either hand blood flow was constricted in both trials and vacuum had no effect, or, hand blood flow already was dilated due to subject hyperthermia and vacuum had no further effect. To test whether the hand was constricted or dilated during cooling, we occluded arm blood flow at the end of each test. Occlusion always caused a marked reduction of NBF at the hand, ranging from 94 to 100% loss of pre-occlusion value. Individually none of these tests conclusively proves a lack of vasoconstriction during RTX cooling, but their combined effect strongly suggests that vasoconstriction did not occur.

Improving palm cooling

In our study, 50 min of continuous PC application caused an initial rapid decline in core temperature (0.23°C over 15 min), and then approached a plateau (decreasing by only 0.14°C over the next 35 min of cooling). We suggest the decreased cooling over time may be related to a reduced gradient for conductive heat transfer from the hand to the cooling plate as the hand cooled. This situation resembles another study that used water perfused vests to reduce heat storage during intermittent work/rest cycles. Here, it was reported that the first 5–10 min of cooling application were the most effective (Constable et al. 1994), after which the time cooling efficiency sharply declined. This was attributed to higher skin perfusion and surface temperature of skin contacting the cooling apparatus. Other authors later showed no difference in heat extraction between liquid cooling garments that were run continuously, or those that were operated intermittently (2 min on/off) (Cheuvront et al. 2003). When taken together, these studies suggest that allowing the palm in contact with the cooling plate to rewarm during operation might also increase heat extraction. This could be accomplished by alternating the hand in contact with the cooling plate, allowing time to reestablish the skin temperature/cooling plate gradient. Further research in this area may be warranted.

Conclusions

In this study, PC significantly reduced thermal strain in passively seated hyperthermic subjects. Negative pressure application during cooling did not increase heat extraction or further reduce thermal strain compared to PC alone. We propose that although PC provided a statistically significant advantage over NC, its application should be considered only in specific conditions where other cooling methods are either impractical or impossible to employ.

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Conflict of interest statement No conflict of interest exists.

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