ORIGINAL ARTICLE

Post-exercise cooling techniques in hot, humid conditions

**Martin James Barwood · Sarah Davey ·
James R. House · Michael J. Tipton**

Abstract Major sporting events are often held in hot and
humid environmental conditions. Cooling techniques have
been used to reduce the risk of heat illness following
exercise. This study compared the efficacy of five cooling
techniques, hand immersion (HI), whole body fanning
(WBF), an air cooled garment (ACG), a liquid cooled
garment (LCG) and a phase change garment (PCG), against
a natural cooling control condition (CON) over two periods
between and following exercise bouts in 31°C, 70%RH air.
Nine males [age 22 (3) years; height 1.80 (0.04) m; mass
69.80 (7.10) kg] exercised on a treadmill at a maximal
sustainable work intensity until rectal temperature (T_{re})
reached 38.5°C following which they underwent a resting
recovery (0–15 min; COOL 1). They then recommenced
exercise until T_{re} again reached 38.5°C and then undertook
30 min of cooling with (0–15 min; COOL 2A), and with-
out face fanning (15–30 min; COOL 2B). Based on mean
body temperature changes (COOL 1), WBF was most
effective in extracting heat: CON 99 W; WBF: 235 W;
PCG: 141 W; HI: 162 W; ACG: 101 W; LCG: 49 W) as a
consequence of evaporating more sweat. Therefore, WBF
represents a cheap and practical means of post-exercise
cooling in hot, humid conditions in a sporting setting.

Keywords Heat-illness · Half-time cooling · Recovery

Introduction

Historically, many major sporting events occur in envi-
ronments that would be regarded as thermally stressful
from the perspective of heat. For example, of the last 6
summer Olympic Games the risk if heat illness, based on
the wet bulb, globe temperature (WBGT, °C), have been
categorised as "very high" in three (Athens, Atlanta, Los
Angeles), "high" in one (Barcelona) and "moderate" in
one (Seoul). This trend continued at the recent summer
Olympics in Beijing, which were held when climatic
conditions were typically 30°C, 70%RH (mean August
daily temperature), giving a risk of heat illness that is
moderate to high. In such conditions, the Heat-Stress Index
predicts the occurrence of heat cramps and heat exhaustion,
and raises possibility of heat-stroke. If the temperature and
humidity had reached record levels, heat stroke was a
definite health risk (Tipton 2006).

At the extreme, heat stroke is a serious medical condi-
tion resulting in collapse (Tipton 2005; Porter 2000). Less
severe heat strain increases the cardiovascular strain asso-
ciated with exercise, diminishes the drive to exercise,
compromises muscle and hepatic blood flow, increases
muscle glycogen utilisation and results in slower perfor-
mance times, and earlier fatigue (Tucker et al. 2006; Nybo
and Nielsen 2001; Gonzalez-Alonso et al. 1999; Rowell
et al. 1966). Therefore, during competition it is important
to delay the onset of heat strain to maximise performance,
and to enhance body cooling during rest periods in sports
which have defined breaks.

It is generally accepted that the optimal cooling strategy
in hyperthermic persons threatened by heat-illness is whole
body cold water immersion (CWI) (Smith 2005). However,
this is not logistically feasible when breaks between halves
or events are short, as clothing removal and re-dressing

M. J. Barwood (✉) · S. Davey · J. R. House · M. J. Tipton
Department of Sport and Exercise Science,
University of Portsmouth, Spinnaker Building,
Cambridge Road, Portsmouth PO1 2ER, UK
e-mail: martin.barwood@port.ac.uk

takes valuable cooling time, or is problematic when large groups of athletes are to be cooled. With this in mind, various strategies have been implemented in an attempt to maintain performance in the heat and regulate body temperature, these include: appropriate pacing (Tucker et al. 2004); clothing design (Lotens and Havenith 1994); acclimatisation/acclimation to heat (Sunderland et al. 2008); hydration strategies (Galloway and Maughan 2000); pre-cooling (Duffield and Marino 2007) and artificial (external) cooling (Mitchell et al. 2001). Techniques for achieving artificial cooling typically utilise smaller body surface areas than that covered during CWI and include: ice vests or phase change garments (PCG; Duffield et al. 2003), jackets or caps (conductive cooling) (Armstrong et al. 1995); air cooled garments (ACG) or fans (convective/evaporative cooling; Chinevere et al. 2008), hand immersion (HI) (conductive cooling; House et al. 2003) and liquid cooled garments (LCG, conductive cooling; Vernieuw et al. 2007).

In some cases (i.e. ACG, LCG), these garments have been developed to combat heat strain in industrial, military and rescue service personnel (Chinevere et al. 2008; Vernieuw et al. 2007). They have been designed to be worn underneath protective clothing, in situations where direct heat exchange with the environment is impaired. In such groups, heat strain is usually caused by restriction of the evaporation of sweat due to the personal protective equipment (PPE). Many separate studies have examined the efficacy of these approaches to cooling and suggest HI to be most effective extracting heat at a rate of 334 W from hyperthermic participants wearing PPE (House 1997; water temperature 10–12°C) during rest periods compared to 20–50 W for ACGs (Reffeltrath et al. 2002), 15–77 W when utilising an LCG (Cadarette et al. 1990) and 72 W in PCGs utilising long chain alkanes (House 2006). However, the different ambient conditions, clothing worn, levels of activity and protocols utilised in these studies makes direct comparison between cooling interventions difficult in either a military or sporting setting.

For athletes the scenario is usually different. With a few exceptions (e.g. fencers, pistol shooters, hockey goal-keepers, American football players), most athletes compete in clothing that does not significantly impede the evaporation of sweat. Additionally, cooling systems designed for use with PPE may not be the most practical or cost-effective method for use in sport. Therefore, as athletes become interested in adopting cooling strategies, they should be aware of the range of equipment available, how it works, for what purpose it was originally developed and whether or not it is be most effective way of addressing their specific needs.

The improvement of comfort during exercise in the heat may also be a goal of utilising supplementary cooling. The use of face fanning is one means of improving comfort prior to, or during, exercise in the heat and may benefit exercise performance (Mundel et al. 2006). Stimulation of cold sensitive thermo-receptors, which are densely distributed over the face, is thought to directly modulate thermoafferent inputs to the hypothalamus, mediating reductions in the neuroendocrine and fatigue responses to exercise in the heat (Armada-da-Silva et al. 2004; Mundel et al. 2006). The perceptual benefit of face fanning may be reflected in lowered perceptions of thermal comfort (TC) and perceived exertion, which can result in exercise performance benefits (Armada-da-Silva et al. 2004).

The present experiment was designed to assess the effectiveness of different cooling techniques at rest following exercise. The cooling periods were similar to those experienced in halftime breaks or intervals. A wide range of cooling techniques commercially available at the time were examined and deployed as per the manufacturers' instructions. These techniques utilised air cooling, liquid cooling and chemical phase change materials. They were compared with the simple, cost-effective methods of HI and whole body fanning (WBF). Each was tested with and without the presence of face-fanning. It was hypothesised that all of the cooling methods would result in faster cooling than that measured in a natural (passive) cooling control condition (CON), with HI being the most effective based on evidence from military based studies. It was also hypothesised that the addition of face fanning would improve TC.

Method

The protocol was approved in advance by the University of Portsmouth Ethics Committee. Having provided written informed consent and having completed a medical examination, nine males [age 22 (3)years; height 1.80 (0.04) m; mass 69.80 (7.10) kg; surface area (DuBois and DuBois 1915) 1.90 (0.10)m^2; sum of skinfolds 34.0 (14.0) mm; body fat 14.4 (4.4)%; Durnin and Womersley 1974] volunteered to participate. They were not heat acclimated but were accustomed to treadmill running. They refrained from strenuous exercise for 72-h prior to experimentation, were non-smokers and abstained from alcohol and caffeine consumption 24 h prior to experimentation.

The study used a within participant repeated measures design in which participants completed self-paced exercise on a treadmill in hot [31.20 (0.20)°C] and humid [70.00 (1.90)% RH] conditions until they reached a rectal temperature of 38.5°C. They then received one of five post-exercise cooling techniques or completed a CON for 15-min (COOL 1). At the end of COOL1 participants recommenced self-paced exercise until their deep body temperature again

reached 38.5°C. This body temperature limit was selected as this is close to the threshold (∼38.7°C) identified as causing premature fatigue in untrained runners (Selkirk and McLellan 2001). They then completed a 30-min period of post-exercise cooling using the same cooling intervention as COOL1, but with (COOL 2A 0–15 min) and without (COOL 2B 15–30 min) the addition of face fanning. The order of exposure to treatment conditions was counterbalanced using a Latin Square.

Procedure

Each participant completed their trials at the same time of day, a minimum of 4 days elapsed between trials to minimise any possible heat acclimation. Upon arrival at the laboratory participants voided, and body mass was measured (naked and clothed mass; Ohaus digital weighing scales, I-10, Canada). Participants wore only underwear, shorts, socks and running shoes; identical clothing was worn for each run. After changing into their running kit, each participant was instrumented. All perceptual scales were explained to each participant before the experiment.

Participants entered the climate chamber and stood on a motorised treadmill (Powerjog GX220, Powerjog, London, UK). Following a verbal countdown, the participant commenced self-paced running at 1% treadmill incline (Jones and Doust 1996). At all times participants had control of the treadmill speed but the treadmill display was masked Each participant ran at their maximal sustainable work intensity until rectal temperature (T_{re}) reached 38.5°C; time, velocity and distance covered were recorded and used as performance measures. Participants then moved to a seated position next to the treadmill (standardised transition period: 3 min) and undertook COOL1.

Following COOL 1 the participant removed the cooling medium (condition dependent) and moved back onto the motorised treadmill (standardised transition period: 3 min) and commenced exercise at a maximal sustainable intensity until T_{re} reached 38.5°C, at this point the participants stopped exercising. If T_{re} did not fall below 38.5°C during cooling the participants ran for 2 min and then stopped. Following cessation of the second period of exercise the participants returned to the seated rest position and commenced a second period of cooling this time for 30 min, divided into two, 15 min periods with (COOL 2A: 0–15 min) and without (COOL 2B: 15–30 min. Figure 1 describes the experiment setup, the details of the conditions were as follows.

Control condition

Each participant sat and rested on a backless chair and did not receive any active cooling or face fanning.

Hand immersion

Each participant sat on the same backless chair and immersed their hands into a water bath (Tempette Junior TE 8 J, Techne, Cambridge, UK) filled with cool tap water (∼17°C) to the level of the wrist (radial notch). Water temperature (T_w) during HI was 17.80 (0.70)°C in COOL 1, 16.40 (0.50)°C in COOL 2A and 16.40 (0.50)°C in COOL 2B; T_w was not different between cooling periods. This temperature was selected as it representative of normal tap and did not require any additional cooling thereby minimising any logistical burden. During HI, participants were reminded to periodically move their hands in the water to prevent any build up of an insulating boundary layer of still

Fig. 1 Diagram depicting the experiment set-up during cooling periods
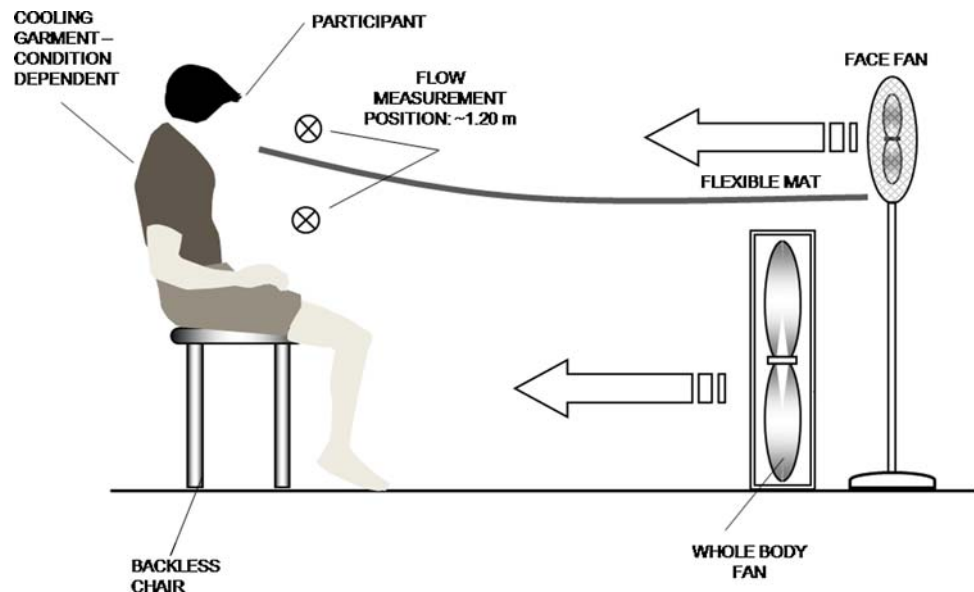
water. Upon removal from the bath participants' hands were dried.

Phase change garment

Each participant donned a vest-styled garment containing two cooling packs inserted into the front and rear of the vest secured in place around the waist with Velcro straps to ensure a close fit to the body surface. At temperatures above 10°C the contents of the panel inserts (long chain alkanes) melt and extract heat (211.7 kJ kg^{-1}), via conduction, from any surface in contact with them. The surface area covered by the PCG was $\sim$0.40 m^2 where the panel inserts covered $\sim$0.23 m^2. The weight of the garment, including two panel inserts, was 3.00 kg. A fresh set of panel inserts was used in COOL 2A.

Air cooled garment

Each participant donned a torso-covering vest secured in place using Velcro straps. At the start of the cooling period both fans, situated front and back, were switched on simultaneously. Each fan distributes ambient air around the vest at a rate of 180 l min^{-1} through a spacer mesh integrated vented system to the torso (including upper shoulder areas). The surface area covered by the ACG was $\sim$0.34 m^2. The weight of the garment, including the fans, was 1.00 kg. The ACG vented system does not cover the Velcro attachment straps ($\sim$0.03 m^2).

Liquid cooled garment

Participants donned a vest secured in place by a zip at the front of the garment. At the start of the cooling period the battery operated cooling system was switched on. The battery pack, ice pack cooling reservoir ($\sim$1.70 l) and pump for the system are contained in a rucksack which was worn by the participant. The system pumps saline ($\sim$500 ml) cooled by the ice pack around a series (24 tubes, 12 parallel channels) of inter-connected cooling tubes sewn into the vest. The inter-connected tubes are flat to ensure maximum contact between the skin and saline circulating around the vest. Upon the attainment of a saline temperature of >12.3°C a thermostat directs the circulating saline through the ice pack thereby cooling the liquid. Until this temperature is reached the saline is not cooled via the ice-pack. The surface area covered by the LCG was $\sim$0.40 m^2; the cooling solution does not circulate around the shoulder area (0.05 m^2). The weight of the garment, including the backpack, saline, filled water reservoir and batteries, was 4.10 kg.

Whole body fanning

Participants were seated in front of fan (Jetstream Mancooler, Colt International Ltd, Hampshire, UK), on fan setting number 2, blowing ambient air at a speed of 3.5–3.80 m s^{-1} onto the torso, arms and legs of the participant; air flow was measured 1.20 m away from the fan in front of the participant. Throughout all conditions, including CON, the head of the participant was isolated from the fan airflow by a flexible mat; this allowed the benefit of face fanning to be assessed separately.

Face fanning

During face fanning air was directed at the face only (Lloytron 16" fan, Model FO59, Lloytron Electronics Ltd) during COOL 2A only. The airflow produced by the fan at 1.20 m distance, at of the level of the head of the participant, was 2–2.5 m s^{-1}. After 15-min of the second bout of cooling the face fan was switched off (minutes 15–30 COOL 2B); a perceptual measure was taken 1-min after the fan was switched off.

At the end of the second cooling bout (COOL 2B; 15–30 min) participants left the environmental chamber, had their instruments removed and were cooled back to pre-exercise T_{re} by seated tepid showering.

Measurements

Skinfold thickness at eight different sites was measured on each participant. Fluid was consumed ad libitum throughout the study and was recorded using digital weighing scales. Fluid intake and pre and post naked and clothed body weights (OHAUS I-10 digital scales, Canada) were used to estimate sweat production and evaporation where evaporated sweat was assumed to be that which did not drip from the participant's body, condense or was not absorbed by clothing. The ambient conditions attained during each trial were recorded every minute using a WBGT weather station (1250 series, Squirrel Data Logger, Grant Instruments Ltd, Cambridge, UK). Water temperature during HI was also recorded every minute using a single thermistor (Grant Instruments Ltd, Cambridge, UK) immersed in the water bath to the level of the hands.

Rectal temperature (T_{re}) was measured with a calibrated thermistor (Grant Instruments, Cambridge, UK) inserted 15 cm beyond the anal sphincter. Skin temperature (T_{sk}) was measured using thermistors (Grant Instruments, Cambridge, UK) attached to the skin by a single piece of Tegaderm^{TM} tape at four sites: chest, arm, thigh and calf (Ramanathan 1964). T_{re} and T_{sk} were recorded each minute on a data logger (1,250/1,000 series, Grant Instruments,

Cambridge, UK). Heart rate was recorded every 6 s using a telemetric data logging system (Polar Team, Electro OY, Polar, UK). Skin blood flow (SkBf) was measured using laser Doppler flowmetry probes (Moor Instruments, Moorlab Satellite, Axminster, UK) attached to the index finger of the right hand and recorded continuously throughout each trial using an analogue to digital data acquisition system (16SP PowerLab, Castle Hill, NSW, Australia). Data were corrected against a biological zero taken at the start of each trial by inflating a blood pressure cuff to 250 mmHg to occlude the brachial artery (House 2006).

Perceptual measures of TC and thermal sensation (TS) were taken every 5 min. TC and TS were assessed using a perceptual scale adapted from the work of Zhang (2003) using a 20 cm sliding scale from Very Uncomfortable (0 cm); Uncomfortable; Just Uncomfortable; Just Comfortable, Comfortable; Very Comfortable (20 cm) for TC and from Very Hot (0 cm); Hot; Warm; Slightly Warm; Neutral; Slightly Cool; Cold; to Very Cold (20 cm) for TS. On both perceptual scales the worded descriptions adjacent to the scale are used as a guide only (Zhang 2003).

Following each trial the participant ranked each of the six cooling interventions (including CON) on a scale of one (best cooling method) to six (worst cooling method).

In the final trial each participant provided a 1-min sample of expired air (Hans-Rudolph Mouthpiece, respiratory tubing, 80L Douglas bag; Harvard Instruments, USA). The sample was taken at the participants' maximal sustainable work intensity typically reached between minutes 5 and 15 of the first exercise bout. The sample was taken to calculate oxygen consumption, using a fast responding gas analyser (Servomex 1400, Servomex, UK) to measure fractional gas concentration and a dry gas meter (Harvard, USA) to measure minute ventilation (V_e). Oxygen uptake (VO_2) was calculated using the Haldane transformation. The metabolic rate was calculated assuming the calorific equivalent per litre of oxygen consumed was 20 kJ where mechanical efficiency was assumed to be 25%. The remainder of the heat was assumed as lost to the environment via convection, conduction, radiation and evaporation.

Calculations

Mean skin temperature was calculated according to the formula:

$$\text{Mean } T_{msk} = 0.3(T_{chest} + T_{arm}) + 0.2(T_{thigh} + T_{calf}) \text{ (Ramanathan 1964)}$$

Mean body temperature was calculated according to the formula:

$$\text{Mean Body temperature}(T_b) = 0.8T_{re} + 0.2T_{msk} \text{ (Colin et al. 1971)}.$$

Stored heat (S) was calculated for each 15 min cooling period (COOL 1, COOL 2A and COOL 2B) using the following equation:

$$S = \Delta T_b \times 3.48 \times \text{mass}/t$$

where: ΔT_b = change in mean body temperature, the average specific heat of body tissues was assumed as 3.48 kJ kg^{-1}°C^{-1} (Pembrey 1898), mass = the pre test mass of the subject (kg), t = time (s)

Statistical analyses

Performance measures

Performance measures including distance covered (km), running velocity (km h^{-1}) and exercise duration (minutes) were compared between cooling interventions and exercise bouts (1 and 2) using Multivariate Analysis of Variance (MANOVA) with repeated measures. Where significant multivariate effects were evident the univariate analysis of variance (ANOVA) statistic was consulted and is reported. Assumptions of sphericity were checked using Mauchley's test. Where non-spherical data sets were evident, as indicated by $P < 0.05$, a Greenhouse–Geisser adjustment was used. The presence of statistically significant effects were determined using a post hoc (least significant difference) pairwise comparisons procedure. Repeated measures ANOVA was also used to examine any differences in self-paced exercise intensity as indicated by the rate of rise in rectal temperature (°C h^{-1}).

Assessment of cooling techniques

Rates of temperature change were calculated for T_{re}, T_{msk} and T_b over 15 (COOL 1, COOL 2A and COOL 2B) and 30 min (COOL 2A + 2B) periods. Statistical comparisons were made between cooling interventions and cooling periods (COOL 1, COOL 2A, COOL 2B and COOL 2A + 2B) using MANOVA according to the same criteria and follow up procedures as outlined above. MANOVA was also used to compare SkBf between cooling interventions across the last 5-min of each cooling period, sweat production and evaporation, average TC, TS and heart rate from each 15 min cooling period. TC was also examined before, 1 min following and 5 min following the switching off of the face fan (RM-ANOVA). The alpha level for all statistical tests was set at 0.05. Where appropriate, data are presented as mean (SD). $P > 0.05$ denotes no significant difference. The observed power, where the chance of

type II error is equal to $1 - \beta$, is reported following each significant finding denoted by β.

Results

During exercise period 1 the average rate of rise in T_{re} was 5.33°C h^{-1} ($N = 54$) and did not differ between conditions ($P = 0.516$; $\beta = 0.144$); all participants had reached a T_{re} of 38.5°C by the 25th min of exercise. In some conditions on some occasions (CON: 2, PCG: 1; ACG: 5; LCG: 4), T_{re} did not fall below 38.5°C after COOL 1 therefore average rate of rise in T_{re} for exercise period 2 are not reported. The average participant, taken from mean body mass pre-exercise (69.80 kg), worked at a metabolic rate of 1,121 (161) W during exercise period 1, assuming 25% mechanical efficiency whilst running, 806 W of this energy will have been expended as heat.

Cooling periods

There were significant differences between condition ($P = 0.001$; $\beta = 0.999$) and between cooling periods ($P = 0.001$; $\beta = 0.984$) in the rates of temperature change observed. Between cooling periods T_{re} ($P = 0.001$; $\beta = 0.999$), T_{msk} ($P = 0.002$; $\beta = 0.951$) and T_b ($P = 0.002$; $\beta = 0.950$) reduced at a faster rate in COOL 2A (with face fanning) than in either COOL 1 or COOL 2B.

In COOL 1 differences in T_{re} ($P = 0.001$; $\beta = 0.999$), T_{msk} ($P = 0.003$; $\beta = 0.930$) and T_b ($P = 0.003$; $\beta = 0.984$) were evident between condition. Statistical findings are presented in the following format, WBF > CON and indicates cooling power of WBF is greater than CON. Only the significant effects are reported. Rates of temperature change for each cooling period for each condition are presented in Table 1 and displayed in Figs. 2 and 3.

The reduction in T_{re} during COOL 1 was greatest in WBF. The differences in COOL 1 were as follows: WBF > CON, PCG, ACG and LCG; HI > CON, PCG and LCG. The reduction in T_{re} in COOL 2A was again greatest in WBF. The differences in COOL 2A were as follows: WBF > CON and LCG. The reduction in T_{re} in COOL 2B was greatest in LCG. The differences in COOL 2A were as follows: LCG > HI; PCG and WBF. Over a 30-min period (COOL 2A + 2B) the reduction in T_{re} was greatest in WBF. The differences in COOL 2A + 2B were as follows: WBF > PCG and LCG.

The reduction in T_{msk} during COOL 1 was greatest in WBF. The differences in COOL 1 were as follows: WBF > CON, HI, ACG and LCG. The reduction in T_{msk} in COOL 2A was greatest in PCG. The differences in COOL 2A were as follows: PCG and WBF > CON, HI, ACG and

Table 1 Mean T_{re}, and T_{msk} differences (°C) between the start and end of the cooling periods during COOL 1, COOL 2A and 2A + 2B

Condition	CON	HI	PCG	ACG	LCG	WBF
COOL1	−0.31	−0.56	−0.31	−0.29	−0.14	−0.63[a]
ΔT_{re}	0.29	0.22	0.26	0.31	0.19	0.24
COOL2A	−0.53	−0.64	−0.53	−0.51	−0.47	−0.66[a]
ΔT_{re}	0.11	0.24	0.19	0.13	0.12	0.15
COOL2A + 2B	−0.76	−0.80	−0.69	−0.76	−0.77	−0.92[a]
ΔT_{re}	0.33	0.31	0.22	0.26	0.19	0.06
COOL1	−0.62	−0.77	−1.38	−0.71	−0.36	−1.83[a]
ΔT_{msk}	0.42	0.23	1.59	0.36	0.86	0.67
COOL2A	0.16	−0.56	−2.21[a]	−0.79	−0.90	−1.83
ΔT_{msk}	0.83	0.35	1.05	0.75	0.66	0.80
COOL2A + 2B	−0.27	−0.78	−2.59[a]	−1.27	−1.30	−1.97
ΔT_{msk}	0.88	0.51	0.74	1.05	0.67	0.54

Significant differences between condition are described in "Cooling periods"

[a] Denotes condition with greatest temperature reduction in each epoch

LCG; ACG and LCG > CON. The reduction in T_{msk} in COOL 2B was greatest in PCG however there were no significant differences in T_{msk} between condition in COOL 2B. Over a 30-min period (COOL 2A + 2B) the reduction in T_{msk} was greatest in PCG. The differences in COOL 2A + 2B were as follows: PCG > CON, HI, ACG, LCG and WBF; WBF > CON, HI, LCG; ACG and LCG > CON and HI. The decline in T_{msk} in each condition is displayed in Fig. 3.

The reduction in T_{body} during COOL 1 was greatest in WBF. The differences in COOL 1 were as follows: WBF and HI > CON, ACG and LCG; WBF > HI. The reduction in T_{body} in COOL 2A was greatest in WBF. The differences in COOL 2A were as follows: WBF > CON, HI, ACG and LCG; PCG > CON, ACG and LCG HI > CON. The reduction in T_{body} in COOL 2B was greatest in ACG however there were no significant differences in T_{msk} between condition in COOL 2B. Over a 30-min period (COOL 2A + 2B) the reduction in T_{body} was greatest in PCG. The differences in COOL 2A + 2B were as follows: PCG and WBF > CON, HI and ACG.

Calculated heat storage, using ΔT_{body}, is reported in Fig. 4.

There were significant differences in average heart rate between cooling periods ($P = 0.001$; $\beta = 999$) but not condition ($P = 0.736$; $\beta = 0.079$). On average heart rate was higher in COOL 1 [116 (3) bt min^{-1}] than both COOL 2A [100 (5) bt min^{-1}] and COOL 2B [100 (5) bt min^{-1}] which were not different.

Fig. 2 Mean T_{re} changes across conditions during COOL 1, 2A and 2B; significant differences ($P < 0.05$) at the end of the cooling periods are summarised (0–15 min COOL 1, 0–15 min COOL 2A and 15–30 min COOL 2B ($N = 9$)
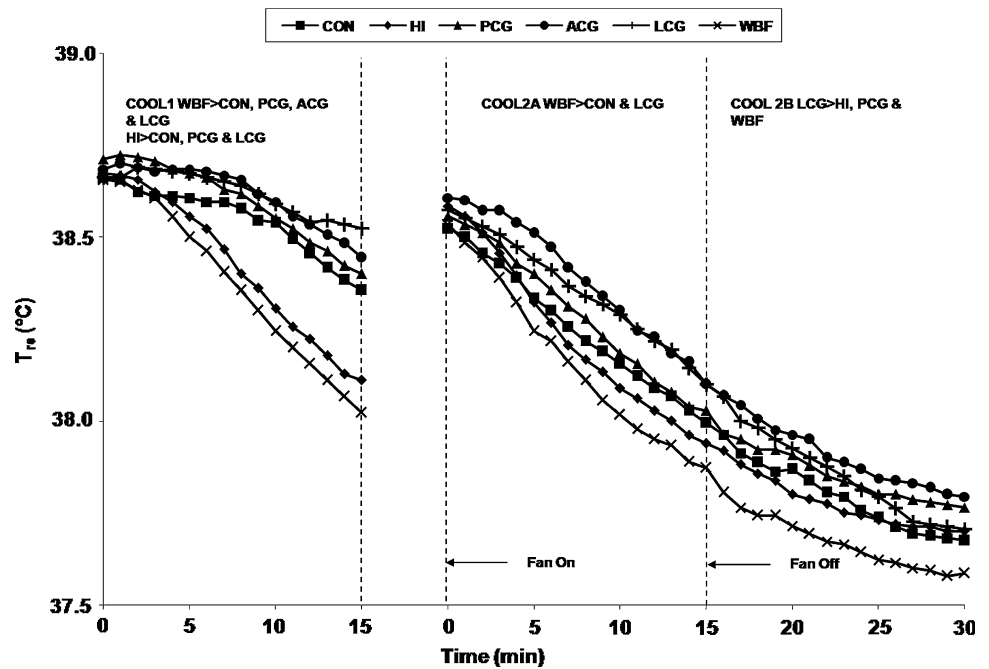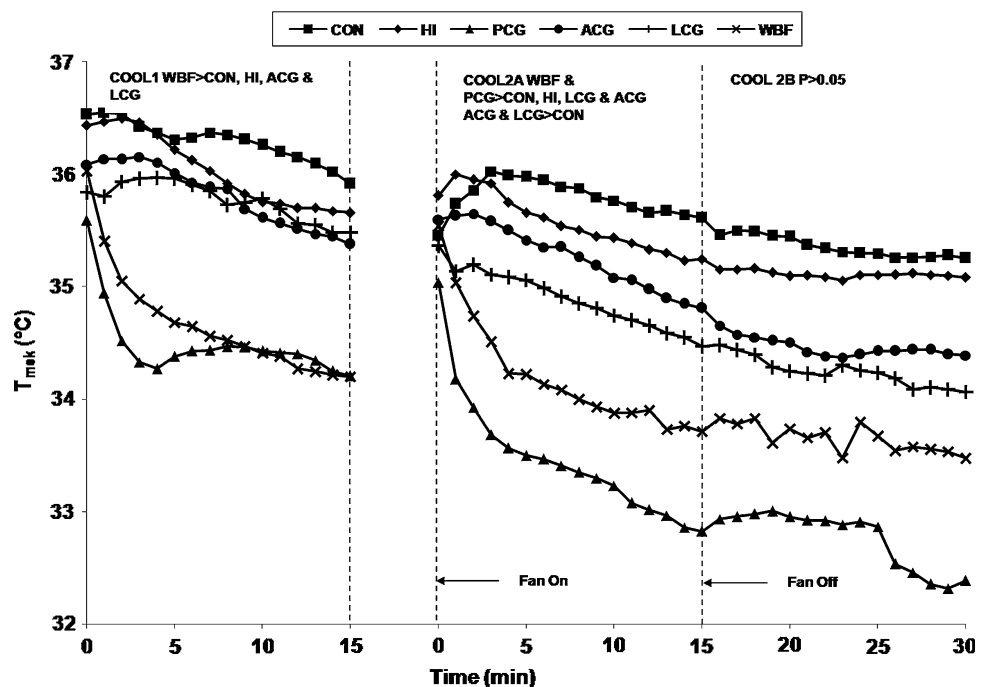

Fig. 3 Mean T_{msk} changes across conditions during COOL 1, 2A and 2B; significant differences ($P < 0.05$) at the end of the cooling periods are summarised (0–15 min COOL1, 0–15 min COOL 2A and 15–30 min COOL 2B ($N = 9$)

Skin blood flow

Skin blood flow showed significant differences between conditions across the last 5-min of each cooling period ($P = 0.005$; $\beta = 0.915$). There were no differences in peripheral blood flow between conditions at the end of COOL 1. At the end of COOL 2A ACG > HI and at the end of COOL 2B index finger blood flow in the PCG, ACG, LCG and WBF > HI (index finger only; Fig. 5). Within condition, blood flow in the HI condition was

significantly lower in the last 5 min of COOL 2B versus COOL 1 ($P = 0.001$; $\beta = 0.999$).

Sweat produced (L), evaporated (%) and fluid consumed (L)

There were no significant differences in sweat produced or fluid consumed between conditions ($P > 0.05$), the average across all conditions was: fluid consumed 792 (262) ml and sweat produced 1001 (210) ml. Sweat evaporated differed

Fig. 4 Comparison of mean cooling power of each cooling intervention in COOL 1 (*black bars*), COOL 2A (*grey bars*) and COOL 2B (*white bars*) (*N* = 9); (*asterisk*) denotes greater cooling power in COOL 1 and COOL 2A (*dagger*)
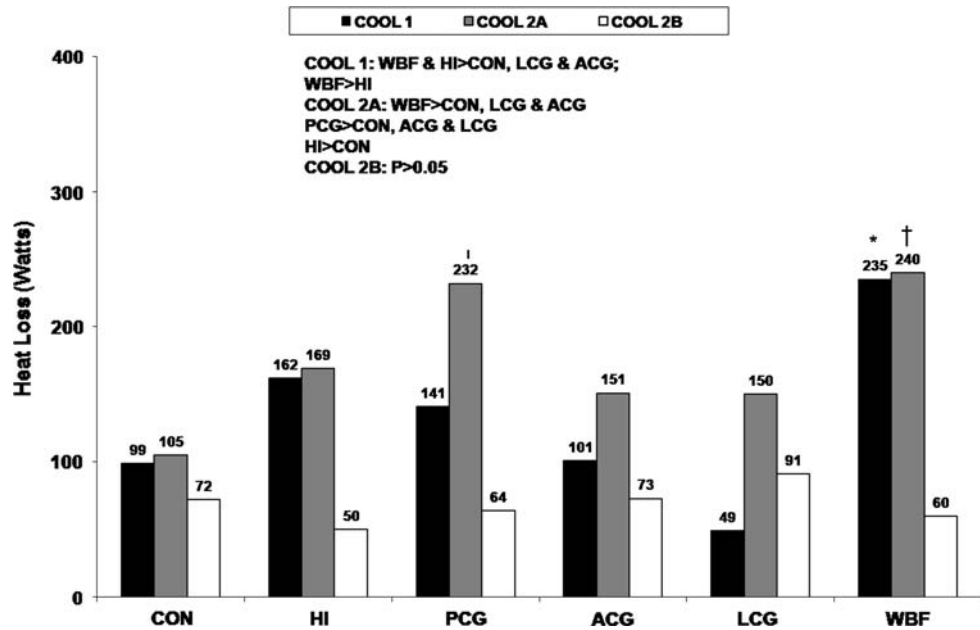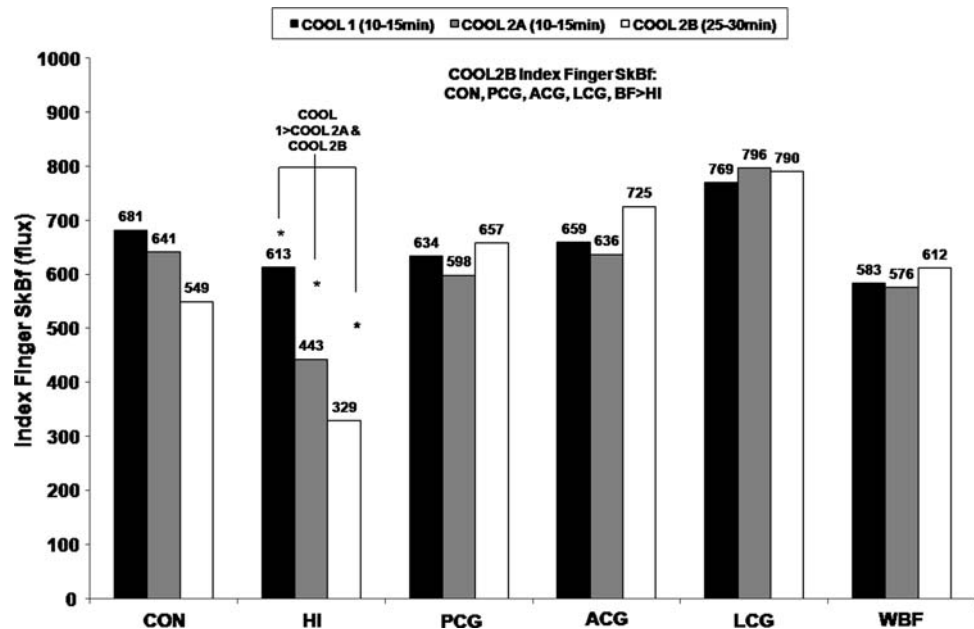

Fig. 5 Comparison of index fingertip SkBF across conditions in the last 5 min of COOL 1, 2A and 2B; significant differences (*P* < 0.05) within HI and at the end of COOL 2B are summarised (*N* = 9)

significantly between conditions ($P = 0.008$; $\beta = 0.888$) showing that significantly more sweat was evaporated in the WBF [90.40 (6.00)%] than the CON [73.90 (11.00)%]. There were no further differences between the condition: ACG [82.20 (4.00)%]; LCG [84.00 (6.00)%]; HI [83.00 (6.00)%]; PCG [82.80 (5.00)%].

Performance measures

Significant exercise bout effects were evident ($P = 0.001$; $\beta = 0.999$) and participants ran for significantly longer [$P = 0.001$; $\beta = 0.924$; exercise 1: 15.33 (0.91) min, exercise 2: 6.00 (1.60) min], further [km: $P = 0.001$; $\beta = 0.937$; exercise 1: 3.30 (0.30) km, exercise 2: 1.20 (0.11) km] and faster [$P = 0.009$; $\beta = 0.597$; velocity 1: 13.40 (0.17) km h^{-1} velocity 2: 11.60 (0.85) km h^{-1}) in exercise bout 1 than bout 2.

There were also exercise bout by condition interactions ($P = 0.011$; $\beta = 0.961$) where exercise duration ($P = 0.001$; $\beta = 0.990$), distance covered ($P = 0.029$; $\beta = 0.778$) but not velocity ($P = 0.271$; $\beta = 0.420$) were different between some conditions in exercise bout 2 only. Differences in distance covered in exercise bout 2 are reported in Fig. 6. After COOL 1, participants ran

Fig. 6 Comparison of mean distance covered following COOL 1 in each cooling condition ($N = 9$); (*asterisk*) denotes significantly greater distance covered than in all other conditions with the exception of PCG
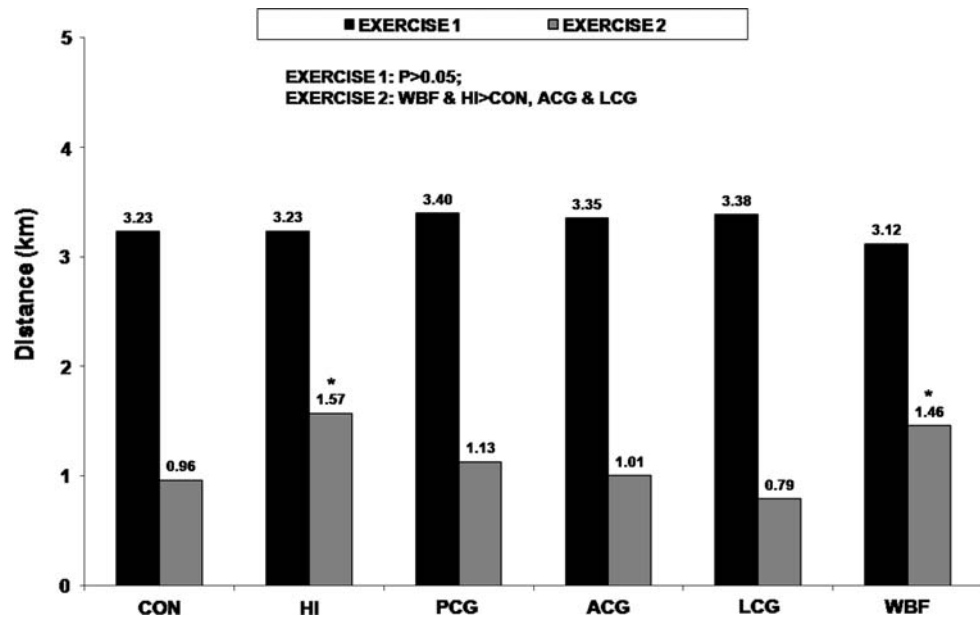
significantly further in the HI and WBF conditions than in the CON, LCG and ACG.

Perceptual effects

There were no significant differences between condition or across time in TS; these analyses neared significance ($P = 0.075$). Mean (SD) TS pooled across all conditions were 13.9 (1.0) in COOL 1 (14 = *slightly warm*), 11.8 (1.3) in COOL 2A and 10.9 (0.9) in COOL 2B (11 = *neutral* to *slightly warm*; 12 = *slightly warm*).

No significant differences were evident between individual cooling conditions in mean TC rating in COOL 2A (face fanning) versus COOL 1 and COOL 2B (no face fanning). Significant differences were evident over time ($P = 0.013$; $\beta = 0.924$), with participants feeling more comfortable during COOL 2B (no face fanning), compared to COOL 2A (face fanning; $P = 0.003$) and COOL 1 ($P = 0.003$); participants had lower body temperatures at this time (Fig. 2). Ratings were COOL 1: 10.8 (0.8)—*just comfortable*; COOL 2A 12.2 (0.6)—*just comfortable* to *comfortable*; COOL 2B 13.4 (0.6)—*just comfortable* to *comfortable*; differences between COOL 1 (no face fanning) and COOL 2A (face fanning) neared significance ($P = 0.077$). After switching off the fan, participants reported being more comfortable ($P = 0.003$; $\beta = 0.978$) in the HI and PCG conditions than in the CON.

Ranking of conditions

The conditions were ranked as follows (*best* to *worst*): PCG [2.00 (1.10)]; BF [2.20 (1.10)]; HI [2.30 (1.20)]; LCG [3.90 (1.10)]; ACG [4.80 (0.80)]; CON [5.80 (0.40)].

Discussion

This study examined the efficacy of five post-exercise cooling strategies. The findings show the most effective form of cooling was body fanning. Phase change chemical blended inserts (PCG) were effective in cooling the skin (Fig. 3), but had a less substantial effect upon deep body temperature (Fig. 2). This latter finding supports that of Duffield and Marino (2007). The remainder of the cooling interventions examined in this study were generally statistically indistinguishable from the CON, particularly during the last 15-min of the 30-min cooling period. When the drop in rectal temperature was examined independent of skin temperature (Fig. 2; COOL 1), HI closely reflected the cooling power of body fanning providing partial support for the experimental hypothesis. However, the reduction in rectal temperature was not consistent across cooling periods and was not (Fig. 2) of the same magnitude as WBF (Table 1).

Some methodological considerations must first be made prior to further interpretation of these data. The site for the measurement of deep body temperature, the rectum, has been noted to be slow responding (Tipton 2006). In the current study, particularly during the first cooling period, the dynamic response of rectal temperature was sufficient to distinguish WBF (COOL 1 and 2A), HI (COOL 1 only) and LCG (COOL 2B; Fig. 2) as providing greater cooling than the other conditions (Fig. 2). Other sites for deep body temperature were discounted on the basis of discomfort (oesophageal), confounding in the presence of face fanning (aural) and potential variability in deep body temperature due to gastrointestinal transit (radiotelemetry pill) (Tipton 2006).

Careful consideration must also be given to the skin temperature data generated from a weighted mean of four sites. The substantial cooling of one thermistor site (chest) may contribute to an overestimation of skin cooling provided by the cooling garments (i.e. PCG, LCG, ACG) which cover only ∼30% of body surface area. The formula used to calculate mean skin temperature also uses a 30% weighting from the chest thermistor site suggesting the cooled surface area is reflected in the mean skin temperature calculation. An accurate skin temperature can only be assumed in hot conditions when skin temperature, and therefore skin blood flow, is uniformly distributed as is the case with hyperthermic participants. In cold conditions blood flow to the periphery (i.e. fingertips, toes, ears), may be sacrificed in order to maintain deep body temperature. Consultation of the fingertip skin blood flow data (Fig. 5) suggest that, despite undergoing a raft of cooling interventions, fingertip blood flow was only reduced in one condition, HI. This is likely to be due to the local influence of the cold water on vasomotor tone. In the remainder of the cooling conditions fingertip blood flow, and therefore the perfusion of the arterio-venous anastomoses, was unchanged. This demonstrates that the thermoregulalory drive from central thermoreceptors is preserved despite auxiliary cooling taking place suggesting that skin temperature is accurately reflected using the present method.

With these methodological considerations made, it appears that the combination of convective and evaporative cooling that is most effective in the conditions of the present test. The remaining cooling interventions predominantly harnessed conductive cooling (HI, PCG and LCG) with HI and PCG proving most effective over 15 min and LCG providing some deep body cooling over 30 min. During HI a conductive gradient was established during the first 15-min of cooling but vasoconstriction (Fig. 5) in the second 15-min of the 30-min cooling period may have impeded further heat loss; this cannot be attributed to low water temperature (unchanged between minutes 0–15 (COOL 2A) and 15–30 (COOL 2B)), but is more likely due to the adjustment of vasomotor tone as deep body temperature cools toward normal levels. This fall is permissive, allowing local skin temperature to produce a vasoconstriction (Bligh 1998). We speculate that, in the PCG local vasoconstriction (i.e. under the vest), although not measured, may also have been influential as deep body temperature did not reduce significantly after 15 min of cooling in this condition. This suggests cutaneous blood flow, and therefore circulating heat exchange, was not preserved under the vest leading to the predominant change only in skin temperature. In the LCG the fall in skin temperature was not as substantial as in the PCG and a gradient for heat loss was eventually established whilst preserving peripheral blood flow (Figs. 2, 5), albeit after 30 min.

In addition to WBF, the ACG also utilised convective and evaporative cooling. This garment was originally designed for use under PPE in the heat and has been reported to be effective in this scenario (Hadid et al. 2008). However, this garment did not rival body fanning for cooling power. This may be due to: the surface area covered by the vest compared to WBF; the insulation provided by wearing the garment; or the general efficacy of the garment cooling system in the conditions of the present test. In this context, it is worth noting that the PCG covered the same surface area of the body as the ACG but was more effective at reducing skin temperature. It is also worthy of note that, all of the interventions that included partial body coverage may have provided additional insulation and impeded sweat evaporation. Indeed when the cooled surface area considered, WBF maximises the potential for heat exchange. In contrast, HI enables a comparable amount of heat to be extracted from the deep body but is outperformed by WBF when the participant is sweating and is wearing no or almost no clothing (Fig. 2). Immersing a greater proportion of the upper limbs (forearms) may enhance the conductive heat exchange.

The hypothesis in relation to face fanning was not supported. However, there was consistent evidence of cooling power being greater in COOL 2 (with face fanning, Figs. 1, 2, 3; Table 1) suggesting that forced convection and sweat evaporation may have been augmented despite attempts to shield the body whilst face fanning. These data make further conclusions based on the independent influence of face fanning on thermal perceptions difficult. Consequently, there was support in only two of the six cooling conditions (HI and PCG only). This suggests that those conditions that include contact with a definitive heat sink, in this case cool water (HI) and phase change material (PCG), preserved comfort rating after the cessation of face fanning. The overall rating of the cooling conditions support this assertion with PCG (ranked 1) and HI (ranked 3) rated as 2 of the top three interventions, despite WBF (ranked 2) being more effective thermally. Thus, the insignificant effect of face fanning in the present study may have been due to the coincidental presence of another cooling intervention. It may also have been due to the absence of additional cool water/mist dispersed into the airflow of the fan as used in previous studies (Armada-da-Silva et al. 2004; Mundel et al. 2006).

From a health-risk perspective, the capability to reduce deep body temperature over a duration similar to that typically allocated between sporting halves or events is of great importance. Heat-illness is closely related to intolerance of high deep body temperature (Smith 2005) and WBF and HI facilitated a reduction of over 0.5°C in rectal temperature in this time. Moreover, the deep body temperature threshold used in the current study is only

representative of an untrained group of participants but not of that likely to be reached during elite level sport (>40°C; Selkirk and McLellan 2001). At higher internal temperatures the cooling powers demonstrated in the present study could be extrapolated to such situations as the thermoregulatory drive would be greater and would allow as much, if not more, heat to be extracted thereby reducing the risk of heat illness. This may be of benefit particularly in those conditions (i.e. HI) where local vasoconstriction took place as vasomotor tone is less likely to be changed by local cold application at higher body temperatures.

From a performance perspective, the significant reductions of skin and body temperature, significantly increased distance covered during running following COOL 1 in the HI and WBF conditions; the remaining conditions did not differ (Fig. 6). The literature evidence for a performance benefit of artificial cooling between events or halves is equivocal with some studies finding no benefit (Duffield et al. 2003; Mitchell et al. 2001) and others finding supporting evidence (Goosey-Tolfrey et al. 2008). The lack of literature agreement is likely to be a function of differing work intensities, environmental conditions and cooling durations employed between studies. The present study controls for these potential difficulties allowing many cooling interventions to be examined using a standardised protocol in similar environmental conditions. However, in the present study it is difficult to determine whether a longer bout of cooling (>15 min) would have revealed performance related effects in the remainder of the conditions tested (i.e. LCG).

From a practical perspective, the finding that WBF is the most effective in terms of physiological cooling is of great logistical importance. With the exception of HI, the other cooling methods involve significant financial expenditure, particularly if multiple units are acquired. A small ratio of fan units to participants could be utilised to provide a significant cooling effect especially when little or no clothing is worn and when no natural ventilation is present; this may be of use particularly in team sports in the half time break period. In situations where additional fanning is not an option (e.g. triathlon events), cooling could be provided using a heat-sink (similar to HI).

In conclusion, this study examined the efficacy of five post-exercise cooling techniques in conditions that pose a significant risk of heat-illness during exercise, in participants wearing athletic clothing and for a duration similar to that allocated between sporting events or halves; the findings could therefore be applied to a variety of sports performed. Our findings did not fully support our hypotheses. Indeed, WBF proved the most effective means of reducing deep and mean body temperature whereas the remaining conditions were predominantly indistinguishable from a control cooling condition. It is therefore concluded that in

the conditions of the present study, WBF provided an effective means of cooling individuals during limited time periods between and following bouts of exercise in the heat.

References

Armada-da-Silva PAS, Woods J, Jones DA (2004) The effect of passive heating and face cooling on perceived exertion during exercise in the heat. Eur J Appl Physiol 91:563–571

Armstrong LE, Maresh CM, Riebe D et al (1995) Local cooling wheelchair athletes during exercise-heat stress. Med Sci Sports Exerc 27:211–216

Bligh J (1998) Mammalian homeothermy: an integrative thesis. J Therm Biol 23:143–258

Cadarette BS, DeCristofano BS, Speckman KL et al (1990) Evaluation of three commercial microclimate cooling systems. Aviat Space Environ Med 61:71–76

Chinevere TD, Cadarette BS, Goodman DA et al (2008) Efficacy of body ventilation system for reducing strain in warm and hot climates. Eur J Appl Physiol 103:307–314

Colin J, Timbal J, Houdas Y et al (1971) Computation of mean body temperature from rectal and skin temperatures. J Appl Physiol 31:484–489

DuBois D, DuBois EF (1915) The measurement of the surface area of man. Int Arch Med 15:868–881

Duffield R, Marino FE (2007) Effects of pre-cooling procedures on intermittent sprint exercise performance in warm conditions. Eur J Appl Physiol 100:727–735

Duffield R, Dawson B, Bishop D et al (2003) Effect of wearing an ice cooling jacket on repeat sprint performance in warm/humid conditions. Br J Sports Med 37:164–169

Durnin JV, Womersley J (1974) Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. Br J Nutr 32:77–97

Galloway S, Maughan R (2000) The effects of substrate and fluid provision on thermoregulatory and metabolic responses to prolonged exercise in a hot environment. J Sports Sci 18:339–351

Gonzalez-Alonso J, Teller C, Andersen SL et al (1999) Influence of body temperature on the development of fatigue during prolonged exercise in the heat. J Appl Physiol 86:1032–1039

Goosey-Tolfrey V, Swainson M, Boyd C et al (2008) The effectiveness of and cooling at reducing exercise-induced hyperthermia and improving distance-race performance in wheelchair and able-bodied athletes. J Appl Physiol 15:37–43

Hadid A, Yanovich R, Erlich T et al (2008) Effect of a personal ambient ventilation system on physiological strain during heat stress wearing a ballistic vest. Eur J Appl Physiol 104:311–319

House JR (1997) The effectiveness of RN protective clothing against burns. J Def Sci 2:205–212

House JR (2006) An investigation into the use of limbs as sites for body cooling and the influence of skin blood flow on body cooling rates. Doctoral dissertation, University of Portsmouth, Portsmouth

House JR, Lunt H, Magness A et al (2003) Testing the effectiveness of techniques for reducing heat strain in Royal Navy nuclear, biological and chemical cleansing stations' teams. J R Nav Med Serv 89:27–34

Jones AM, Doust JM (1996) A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. J Sports Sci 14:321–327

Lotens WA, Havenith G (1994) Effects of moisture absorption in clothing on the human heat balance. Ergonomics 38:1092–1113

Mitchell JB, Schiller ER, Miller JR et al (2001) The influence of different external cooling methods on thermoregulatory responses before and after intense intermittent exercise in the heat. J Strength Cond Res 15(2):247–254

Mundel T, Hooper PL, Bunn SJ et al (2006) The effects of face cooling on prolactin response and subjective comfort during moderate passive heating in humans. Exp Physiol 91:1007–1014

Nybo L, Nielsen B (2001) Hyperthermia and central fatigue during prolonged exercise in humans. J Appl Physiol 91:1055–1060

Pembrey MS (1898) Animal heat. In: Schafer EA (ed) Textbook of physiology. Hodder and Stoughton, London, p 838

Porter AMW (2000) The death of a British officer-cadet from heat illness. Lancet 355:569–571

Ramanathan NL (1964) A new weighting system for mean surface temperature of the human body. J Appl Physiol 19:531–533

Reffeltrath P, Daanen H, den Hartog E (2002) Efficiency of an individual air-cooling system for helicopter pilots. In: Tochihara Y et al (eds) Proceedings of the 10th international conference on environmental ergonomics. University of Fukuoka, Fukuoka, p 547

Rowell LB, Marx HJ, Bruce RA et al (1966) Reductions in cardiac output, central blood volume, and stroke volume with thermal stress in normal men during exercise. J Clin Invest 45:1801–1806

Selkirk GA, McLellan TM (2001) Influence of aerobic fitness and body fatness on tolerance to uncompensable heat stress. J Appl Physiol 91:2055–2063

Smith JE (2005) Cooling methods used in the treatment of exertional heat illness. Br J Sports Med 39:503–507

Sunderland C, Morris JG, Nevill ME (2008) A heat acclimation protocol for team sports. Br J Sports Med 42:327–333

Tipton MJ (2005) Environmental factors. In: Whyte GP, Harries M, Williams C (eds) ABC of sports medicine. Blackwell Publishing, Cambridge, pp 58–66

Tipton MJ (2006) Thermal stress and survival. In: Rainford DJ, Gradwell DP (eds) Ernsting's aviation medicine. Hodder Arnold, London, pp 213–229

Tucker R, Rauch RL, Harley YX et al (2004) Impaired exercise performance in the heat is associated with the anticipatory reduction in skeletal muscle recruitment. Pflugers Arch 448:422–430

Tucker R, Marle T, Lambert E et al (2006) The rate of heat storage mediates an anticipatory reduction in exercise intensity during cycling at a fixed rating of perceived exertion. J Physiol 574:905–916

Vernieuw CR, Stephenson LA, Kolka MA (2007) Thermal comfort and sensation in men wearing a cooling system controlled by skin temperature. Hum Factors 49:1033–1044

Zhang H (2003) Human thermal sensation and comfort in transient and non-uniform thermal environments. Doctoral dissertation, University of California, Berkley