The effects of different air velocities on heat storage and body temperature in humans cycling in a hot, humid environment

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Abstract

Aim: The purposes of this study were to determine (i) the effects of different facing air velocities on body temperature and heat storage during exercise in hot environmental conditions and (ii) the effects of ingesting fluids at two different rates on thermoregulation during exercise in hot conditions with higher air velocities.

Methods: On five occasions nine subjects cycled for 2 h at 33.0 ± 0.4 °C with a relative humidity of 59 ± 3%. Air velocity was maintained at 0.2 km h^{-1} (0 WS), 9.9 ± 0.3 km h^{-1} (10 WS), 33.3 ±2.2 km h^{-1} (100 WS) and 50.1 ± 3.2 km h^{-1} (150 WS) while subjects replaced 58.8 ± 6.8% of sweat losses. In the fifth condition, air velocity was maintained at 33.7 ± 2.2 km h^{-1} and subjects replaced 80.0 ± 6.8% of sweat losses (100.80 WS).

Results: Heat storage, body temperature and rating of perceived exertion were higher in 0 and 10 WS compared with all other conditions. There were no differences in any measured variable between 100 and 150 WS, or between 100 and 100.80 WS. Thus, the evaporative capacity of the environment is increased with higher air velocities, reducing heat storage and body temperature. At higher air velocities, a higher rate of fluid ingestion did not influence heat storage, body temperature or sweat rate.

Conclusion: The finding of previous laboratory studies showing a beneficial effect of high rates of fluid ingestion on thermoregulation during exercise in hot, humid, windstill conditions cannot be extrapolated to out-of-doors exercise in which facing air velocities are seldom lower than the athlete's rate of forward progression.

Keywords air velocity, dehydration, evaporation, exercise, heat storage, thermoregulation.

Laboratory studies have established that increasing levels of dehydration lead to a proportional increase in body temperature during exercise (Montain & Coyle 1992b). This has been established across a range of environmental temperatures from 22 to 44.4 °C (Pearcy *et al.* 1956, Ekblom *et al.* 1970, Myhre *et al.* 1979). Accordingly it has been concluded that dehydration is one of the most important factors influencing heat regulation during exercise (Sawka 1992, Convertino *et al.* 1996, Galloway & Maughan 1997). However, this specific effect of mild dehydration has been found only in specific laboratory conditions and in runners who lost more that 3% of body weight in a 32 km footrace (Wyndham & Strydom 1969). Other field studies of athletes involved in competitive marathon (Noakes *et al.* 1991), ultramarathon (Noakes *et al.* 1988) and ultratriathlon (Sharwood *et al.* 2002, 2004) events found no such relationship.

An important difference between exercise in the laboratory and out-of-doors is that indoor exercise is more likely to occur in near windstill conditions unless specific equipment is used to produce an adequate facing windspeed, equivalent to what might be expected in out-of-doors exercise. The presence of an adequate windspeed will influence the extent of heat loss by both convection and evaporation. Indeed, the three laboratory studies which reported a relationship between increasing levels of heat storage and dehydration were performed in conditions of low windspeed. Montain & Coyle (1992b) studied a group of elite cyclists able to sustain a high workrate in conditions of 33 °C and 50% relative humidity (RH), but with an air velocity of only 8.6 km h^{-1}. Costill *et al.* (1970) studied athletes running at 70% VO_{2max} in conditions of 25 °C and 50% RH, but with an air velocity of only 5.7 km h^{-1}. Gisolfi & Copping (1974) also examined athletes running at a high velocity (12.8 and 14.4 km h^{-1}) in hot conditions of 33.5 °C and 38% RH, but with an air velocity of only 2.16 km h^{-1}.

The important practical point is that, based on these laboratory experiments (Costill *et al.* 1970, Gisolfi & Copping 1974, Montain & Coyle 1992b) in which convective and evaporative cooling was likely to be less than those encountered in out-of-doors competition, the American College of Sports Med (ACSM) has adopted fluid replacement guidelines that advocate ingesting large amounts of fluid in order to prevent any weight loss during exercise. This advice is based on the conclusion that only complete fluid replacement maintains the lowest body temperature during exercise in the heat. Yet, those studies invite the hypothesis that the elevated body temperature measured with increasing levels of dehydration may have been caused by the limited capacity of the hot, wet environment to absorb the heat produced at high rates by well-trained athletes exercising in unnatural conditions caused by a low facing windspeed.

An alternative possibility is that the different thermoregulatory responses to dehydration during laboratory exercise might result from the lower capacity for convective and evaporative heat loss due to the relatively windstill conditions used in these studies. Indeed, evaporative heat loss is the most important form of heat loss, especially in hot conditions (Pitts *et al.* 1944, Katch & Katch 1974, Dennis & Noakes 1999). Furthermore, since air velocity substantially influences potential rates of both convective and evaporative heat loss (Nielsen 1996), the absence of an adequate facing windspeed is likely to affect heat storage in the body by reducing the capacity for heat loss by evaporation and convection. Elite cyclists ride at speeds ranging from 20 to 50 km h^{-1} and would, therefore, generate an equivalent facing windspeed; yet cycling experiments investigating the thermoregulatory effects of dehydration have used low air velocities of 0–8.6 km h^{-1} (Ekblom *et al.* 1970, Barr *et al.* 1991, Nicol *et al.* 1991, Montain & Coyle 1992a,b). The potential effect of such low air velocities has been investigated by Adams *et al.* (1992), who showed that subjects reached higher rectal and oesophageal temperatures when they exercised in windstill conditions compared with a facing air velocity of 12.6 km h^{-1}. This air velocity was created by fans, presumably of the large industrial type, but only one velocity was studied and this was still substantially lower than velocities experienced in competitive cycling.

Accordingly, the first aim of this study was to evaluate the effects of different facing air velocities on body temperature and heat storage in subjects who cycled for 2 hours at a constant power output (183 ± 32 W) in hot conditions while they replaced 60% of their weight losses. The range of air velocities tested compares traditionally used windspeeds in laboratory studies with air velocities encountered during actual out-of-doors cycling exercise. We hypothesized that the extent of body temperature elevation and heat storage would decrease at higher air velocities due to an increased capacity of the environment to absorb heat transferred from the exercising humans by convection and evaporation.

The second aim of this study was to determine whether the rate of fluid ingestion equivalent to either 60 or 80% of weight losses influenced body heat storage when the facing air velocity equalled 100% of the subjects' calculated road speed (33.6 ± 2.3 km h^{-1}) at the power output corresponding to 60% of their peak power output (PPO) (Di Prampero *et al.* 1979). Montain and Coyle showed that rectal temperatures were significantly different when the difference in fluid replacement was 33% between conditions. We hypothesized that the higher rate of fluid ingestion would not further enhance thermal balance in conditions in which appropriate air velocities were studied.

Methods

Subjects

Nine moderately trained cyclists were recruited for this study and completed the experimental protocol. The mean age, height, mass, and PPO of the subjects were 30.2 ± 7.1 (SD) years, 173.7 ± 5.2 cm, 71.5 ± 6.8 kg and 304.7 ± 53.5 W respectively. The study was performed according to the Declaration of Helsinki and was approved by the Research and Ethics Committee of the Faculty of Health Sciences of the University of Cape Town (REC REF 174/2002). All subjects were informed of the procedures and risks of the trials both verbally and in writing, and written consent was obtained from each subject prior to any exercise testing. Each subject was informed that he was free to withdraw from the trial at any time.

Preliminary testing

At the initial visit, anthropometric data and training history were recorded. Peak power output of each subject was determined using an incremental continuous protocol (Hawley & Noakes 1992) performed on a stationary electro-magnetically braked cycle ergometer (Lode, Groningen, The Netherlands). Briefly, subjects started at a workload of 3 W kg^{-1}, which was increased by 25 W each 2.5 min until exhaustion. Exhaustion was defined as the inability of the rider to maintain 60 rpm, or when the subject stopped voluntarily. Subjects' maximum rates of oxygen consumption (VO_{2max}) were predicted according to the equation of Hawley & Noakes (1992). Subjects were required to remain seated throughout the test.

One to 3 days later, subjects completed a familiarization procedure, in which they cycled for 1 h at 60% of PPO on the Lode ergometer in the environmental chamber at 33 °C with a RH of 60% and an air velocity of 8.6 km h^{-1}. For all subsequent experimental trials, subjects cycled for 2 h, and all procedures and conditions were repeated except for the windspeed, and the fluid ingestion rates, which were determined based on the familiarization trial so that at least 60% of each subject's weight losses would be replaced during the subsequent trials. Subjects reported to the laboratory and were weighed nude on a scale accurate to 100 g before each trial (Model 770; Seca, Bonn, Germany), including the familiarization trial. Subjects were allowed to drink *ad libitum* during the familiarization trial, and the volume of fluid ingested was recorded. Upon completion of the trial, subjects towelled dry and weighed themselves. The subject's sweat rate was estimated as

$$\text{Sweat rate } (\mathrm{L\,h^{-1}}) = [\text{Pre-BW (kg)} + \text{fluid ingested (L)} - \text{post-BW (kg)}]$$

This calculation does not take into account weight loss due to irreversible fuel oxidation and respiratory fluid loss, since it was assumed that these would not differ between trials.

Sixty (or eighty per cent for 100.80 WS condition) per cent of this value was determined, and this volume of fluid was divided equally into six smaller volumes, which were ingested at 5, 20, 40, 60, 80 and 100 min during the subsequent experimental trials (Montain & Coyle 1993). The subjects were allowed 5–10 min to ingest the fluid, since it could not be consumed at once. Fluid was ingested at room temperature for all trials (20–24 °C) (Wimer *et al.* 1997).

Experimental design

The study was performed in a randomized cross-over design, with each subject cycling for 2 h on five separate occasions under different environmental conditions in a specially constructed environmental chamber (Scientific Technology Corporation, Cape Town, South Africa) specifically designed to ensure uniform air movement through the entire chamber at the required air velocity, thereby reproducing more closely the conditions experienced during out-of-doors exercise. The order of testing was counterbalanced in order to account for any training or acclimatization effect. All trials were performed in conditions of 33 ± 0.4 °C and 59 ± 3% RH. Trials were separated by a minimum of 3 days to minimize acclimatization and to provide adequate recovery between trials. Each subject performed all the trials at the same time of day to avoid diurnal variations in body temperature, and all testing was performed during the winter months.

During the first four conditions, subjects replaced 60% of weight losses and the air velocity was maintained at either 0.2 km h^{-1} (0 WS condition), 10 km h^{-1} (10 WS condition), 100% of calculated road speed (100 WS condition) and 150% of calculated road speed (150 WS condition), based on the equation of Di Prampero *et al.* (1979). In the fifth condition, subjects replaced 80% of weight losses, while the air velocity was controlled at 100% of calculated road speed (High fluid intake condition, 100.80 WS). Subjects ingested a commercially available 7% carbohydrate electrolyte solution (Energade) during the experiments. Subjects stopped cycling after 2 h or when the rectal temperature reached 40 °C.

Protocol

Subjects arrived at the laboratory 30 min before the scheduled start of the experiment in a euhydrated condition. Euhydration was achieved by ingestion of 5 mL kg^{-1} bodyweight of water 2 h before the start of exercise (Montain & Coyle 1992b). If the trials were performed in the early morning, this volume was consumed upon waking. Euhydration was confirmed by a body weight within 200 g of the preceding trials, a resting rectal temperature of within 0.2 °C of the preceding trials, and a resting heart rate within six beats of the previous trials, according to previously described methods (Montain & Coyle 1992b, Lambert *et al.* 1998).

The subject then inserted a rectal thermometer (YSI 409AC; Yellow Springs Instruments, Yellow Springs, OH, USA) 10 cm beyond their anal sphincter, and four surface thermocouples (YSI 427; Yellow Springs Instruments) were securely attached to the arm, chest, thigh and calf (positioning described later). Thereafter the subject entered the environmental chamber and the equipment was attached to a digital telethermometer, accurate to 0.1 °C (YSI 400 series; Yellow Springs Instruments).

Resting values for temperature and heart rate were recorded in still conditions within 2 min of entering the chamber, before adjusting the air velocity. The air velocity was increased shortly before the start of the trial, and reached the required speed within 1 min of the start of the trial. During each trial, rectal temperature, skin temperatures were recorded at 2 min intervals for subsequent calculations.

Environmental conditions including air temperature (T), RH and air velocity (WS) were recorded at 5 min intervals.

Heart rate was recorded every 2 min using a Polar Accurex NV heart rate monitor (Polar Electro OY, Kempele, Finland).

A subjective rating of perceived exertion (RPE) was recorded every 10 min using the Borg Category Ratio Scale (Borg 1982).

Immediately following exercise, the subjects exited the environmental chamber, and the skin thermisters were rapidly removed. The subject then entered an adjoining room, removed the rectal probe and all clothing, towelled dry and recorded a post-exercise nude body weight (post-BW).

Calculations and equations

Calculation of facing air velocities equivalent to cyclist's average power output. The approximate air velocities for the different trials were estimated from the power output of the cyclist using the equation of Di Prampero *et al.* (1979):

$$W = 3.2s + 0.0725(P_B/T)v^2 s,$$

in which W is the work output in watts, s the ground speed in m s^{-1}, v the velocity of the cyclist in m s^{-1}, P_B the barometric pressure in Torr, and T absolute air temperature in K. In calm air, therefore, ground speed (s) equals the velocity of the cyclist (v). The temperature was maintained at 33 °C (306 K) and the barometric pressure was 760 Torr. The daily variation in barometric pressure was ignored as it became insignificant when compared with the variation in the air velocity. The equation was therefore reduced to:

$$W = 3.2v + 0.0725(2.484)v^3,$$

which was then solved to calculate v for each subject. This equation gives the air velocity which would be encountered during cycling in windstill conditions in out-of-doors exercise.

Four fixed large fans, each with a fan diameter of 1.0 m located in the chamber in front of the cyclist created the air velocity. The environmental chamber is designed as a continuous, circular corridor so that the fans circulate a moving volume of air around a central partition, resulting in all the air in the chamber being in constant motion at the selected windspeed. This closely simulates the effect of riding out of doors, thereby maximizing the potential for convective and evaporative heat loss.

Measurement of body temperature. Rectal temperature was recorded using a rectal thermometer inserted to 10 cm past the anal sphincter. Skin temperature was measured using skin thermocouples at four sites: lateral upper arm; chest at a point midway between the acromium process and the nipple; midway up the lateral side of the thigh; and on the lateral side of the upper calf. Mean skin temperature was calculated according to the equation of Ramanathan:

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

(Ramanathan 1964, Mitchell & Wyndham 1969)

Mean body temperature was calculated according to the weighting factors for exercise in a hot environment:

$$T_{body} = 0.79(T_{rec}) + 0.21(T_{sk})$$

(Colin *et al.* 1971)

Weight loss replacement. The percentage weight loss replaced was calculated according to the following equation, and corrected for exercise time:

$$\%\text{Weight loss replaced} = 100 \times \text{total volume intake (L)}/\text{sweat volume (L)}$$

Heat storage. Heat storage was calculated for the exercise interval using the following formula:

$$H_S = 0.965 \times \text{BW} \times T/A_D,$$

in which H_S is the storage in W m^{-2}, T the change in body temperature, BW the mean body mass over duration of trial in kg, A_D the body surface area in m^2, 0.965 the specific heat capacity of the body in W kg^{-1} °C (Adams *et al.* 1992). The value for heat storage was then divided by the duration of each trial to calculate the rate of heat storage per hour.

Body surface area (A_D). Body surface area (A_D) was calculated according to the formula of Du Bois & Du Bois (1916):

$$A_D = 0.202\text{BW}^{0.425} \times \text{height}^{0.725},$$

(Du Bois & Du Bois 1916) in which A_D is the body surface area in m^2, BW the mean body mass over duration of trial in kg, height is the subject height in m.

Radiative heat loss. T_r (radiant temperature) is defined as the temperature of an imaginary isothermal 'black' enclosure which will give the same radiant heat exchange as the actual ambient conditions in question. For most indoor environments, however, T_r is very close to T_{db}, and therefore $T_r = T_{db}$ (Kenney 1998). Therefore, radiant heat exchange can be calculated using the following formula:

$$R = 4.7(T_{db} - T_{sk}),$$

in which R is the radiative heat loss in W m^{-2}, 4.7 the radiative heat exchange coefficient in W m^{-2} °C, T_{db} the dry bulb temperature in °C, and T_{sk} the average skin temperature in°C. (Kenney 1998).

Convective heat loss. Convective heat loss in still air (0 WS) was calculated according to the following equation:

$$C = 6(T_{sk} - T_{db}),$$

in which C is the convective heat loss in W m^{-2}, 6 the heat transfer coefficient in W m^{-2} °C, T_{sk} the average skin temperature in °C, and T_{db} the dry bulb temperature in °C (Adams *et al.* 1992).

In moving air, the following formula was used:

$$C = 8.3 \times v^{0.6} \times (T_{sk} - T_{db}),$$

where 8.3 is the convective coefficient for heat exchange in W m^{-2} °C, v is velocity of moving air over the body in m s^{-1} (Kenney 1998).

Evaporative heat loss. Evaporative heat loss was calculated according to the equation

$$E = (P_{sk} - P_a) \times v^{0.5} \times 124.$$

In which E is the evaporative heat loss in W m^{-2}, P_{sk} the saturated water vapour pressure at skin temperature in kPa, P_a the ambient water vapour pressure in kPa, v the air velocity moving over the subject in m s^{-1}, 124 the evaporative coefficient for heat exchange in W m^{-2} kPa $v^{0.5}$ (Dennis & Noakes 1999).

In still air, air velocity is used as 0.75 km h^{-1} (0.2 m s^{-1}) due to the moving air created by the movement of the legs (Adams *et al.* 1992).

Saturated water vapour pressure. The saturated water vapour pressure and ambient water vapour pressure used in the above equation were calculated from ambient temperature, average skin temperature and RH using the following equations:

$$P_{sa} = e\{18.956 - [4030.18/(T_{db} + 235)]\}.$$

In which P_{sa} is the saturated water vapour pressure in mmHg T_{db} the dry bulb temperature in °C (Kenney 1998). mmHg were converted to kPa by dividing by 7.5.

$$7.5 \text{ mmHg} = 1 \text{ kPa}$$

$$RH = P_a/P_{sa} \times 100$$

(Kenney 1998).

Statistical analysis

All statistical analysis was performed using Statistica 6.0 (Statsoft1284-2001, Tulsa, Oklahoma, USA). Data are shown as mean ± SD where appropriate. Rectal, skin and calculated body temperatures, heat storage, heart rates and RPE values were analysed using a repeated measures ANOVA to examine interactions between windspeed and time. Where a significant effect was detected, *post-hoc* comparisons were made with a Tukey's HSD for pairwise comparisons. A paired *t*-test was used to analyse pre- and post-body weight differences within a single trial. To analyse differences between the 100 and 100.80 WS conditions, a repeated measures ANOVA (fluid × time) was used. A Pearson's correlation coefficient was used to determine test for correlations. Differences were deemed to be significant when $P < 0.05$.

Results

Manipulation of facing air velocity

In the experiments in this part of the study, subjects ingested a constant volume of fluid while the environmental air velocity was altered between conditions.

Under each condition, subjects were required to ride for 2 h. However, the conditions were designed such that subjects would not be able to achieve heat balance during all the trials. Since subjects were forced to terminate exercise whenever their rectal temperatures reached 40 °C, not all subjects completed all the trials. No subjects completed the 0 WS condition trial, so that the mean (±SD) cycling time was 76.7 ± 16.9 min. Six subjects completed the 10 WS condition (108.4 ± 18.2 min), eight completed the 100 WS condition (116.7 ± 10.0 min) and all subjects completed the 150 WS condition. As a result, the analysis on each time interval is carried out only until the time point at which the first subject terminated the exercise bout. Therefore, analysis of 0 WS condition is performed only until 50 min, until 70 min in the 10 WS condition and until 90 min in the 100 WS condition. The analysis of results for 100 WS over the full 120 min did not alter the findings.

Heat storage over the course of the trial decreased significantly with increasing air velocity so that heat storage was significantly higher in the 0 WS condition compared with all the other conditions (0 WS = 80.8 ± 22.4 vs. 10 WS 42.5 ± 17.2, 100 WS =

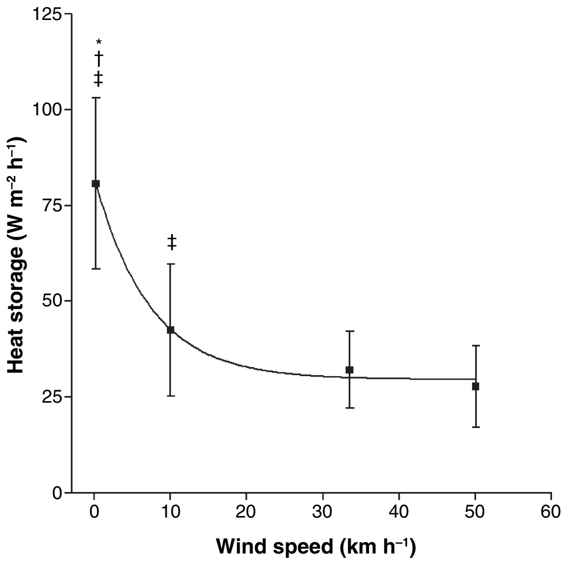

Figure 1 Calculated heat storage expressed per hour during trials with different air velocities. 0 WS = 0 km h^{-1}, 10 WS = 10 km h^{-1}, 100 WS = 33.5 km h^{-1}, 150 WS = 50.1 km h^{-1}. Values are mean values ± SD for nine subjects. *Significantly different from 10 WS ($P < 0.005$); †significantly different from 100 WS ($P < 0.005$); ‡significantly different from 150 WS ($P < 0.05$).

32.1 ± 10.1, 150 WS 27.8 ± 10.6 W m^{-2} h^{-1}; $P < 0.005$, Fig. 1). Heat storage in the 10 WS condition was not significantly different from the 100 WS, but was significantly more than in the 150 WS condition ($P < 0.005$). Heat storage was not significantly different between the 100 and 150 WS conditions (Fig. 1). Heat storage showed a significant correlation with skin temperature ($P < 0.05$). Heat storage was correlated to wind speed using non-linear regression ($R^2 = 0.99$, $P < 0.05$).

No significant differences were observed in the starting mean body temperatures between any of the experimental conditions. The mean body temperature rose significantly in all conditions ($P < 0.05$). Mean body temperature was significantly higher from 10 to 50 min in 0 WS than in 150 WS ($P < 0.05$, Fig. 2a), and was significantly higher from 20 min onwards in 0 WS compared with 10 and 100 WS ($P < 0.02$ and $P < 0.002$). The mean body temperature was higher throughout the experiment in 10 WS than in 100 WS although not significantly. Mean body temperature was higher in 10 WS than in 150 WS from 50 to 70 min ($P < 0.03$). Mean body temperatures were not significantly different between 100 and 150 WS conditions at any time (Fig. 2a).

Rectal temperatures (Fig. 2b) showed the same response as did the mean body temperatures. There were no significant differences in rectal temperature between conditions at the start of the experimental trials. Rectal temperature rose at a faster rate in 0 WS than in the other conditions, and was significantly higher than in 10 and 150 WS from 30 min onwards, and significantly higher than 100 WS at 40 and 50 min ($P < 0.04$). There were no significant differences in rectal temperature between the 10, 100 and 150 WS at any time (Fig. 2b).

Mean skin temperatures were not significantly different between conditions at the start of the experimental trials. Mean skin temperature rose significantly from the starting temperature only in 0 and 10 WS conditions (Fig. 2c). Skin temperature in 0 WS increased significantly with time ($P < 0.01$) and was significantly greater compared with the other three conditions from 10 to 50 min ($P < 0.01$). Skin temperature in 10 WS was significantly higher than 100 WS at 10 and 20 min, and again from 50 to 70 min ($P < 0.01$), and was significantly higher than 150 WS from 10 min onwards ($P < 0.003$). Skin temperature in 10 WS condition rose at the start of the trial, but then levelled off from 10 min until the completion of the trial. There were no significant differences at any time between mean skin temperatures in the 100 WS or the 150 WS conditions (Fig. 2c).

Heart rate was not significantly different between conditions at the start of the trial or after 10 min (Fig. 2d). Heart rate was significantly greater in 0 WS was than in 150 WS from 20 min onwards ($P < 0.009$), and was greater than 10 and 100 WS from 30 min onwards ($P < 0.04$ and $P < 0.005$, respectively). There was no significant difference in heart rate between 10, 100 and 150 WS (Fig. 2d). There was a wide range of individual responses to the conditions with the change in heart rate from rest to finish ranging from 77 to 121 b min^{-1}. The final heart rate was significantly higher in the 0 WS condition despite the shorter duration of exercise ($P < 0.03$).

RPE were not significantly different for the first 20 min between conditions. From 30 to 50 min, RPE in 0 WS was significantly greater than in 150 WS ($P < 0.02$). RPE was significantly increased in 0 WS compared with 10 and 100 WS at 40 and 50 min ($P < 0.03$ and $P < 0.005$, respectively). RPE in 10 WS was significantly greater than 150 WS at 70 min ($P < 0.02$) (Fig. 2e).

Since not all the subjects managed to complete the 2 h of the trial, fluid intake and % body weight loss are corrected for time by dividing total sweat loss by exercise duration to enable comparison between conditions (Table 1). There were no significant differences in the pre-exercise body weights between conditions. The post-exercise body weight was significantly lower than the pre-exercise body weight in all conditions ($P < 0.00006$). The total fluid replacement during trials

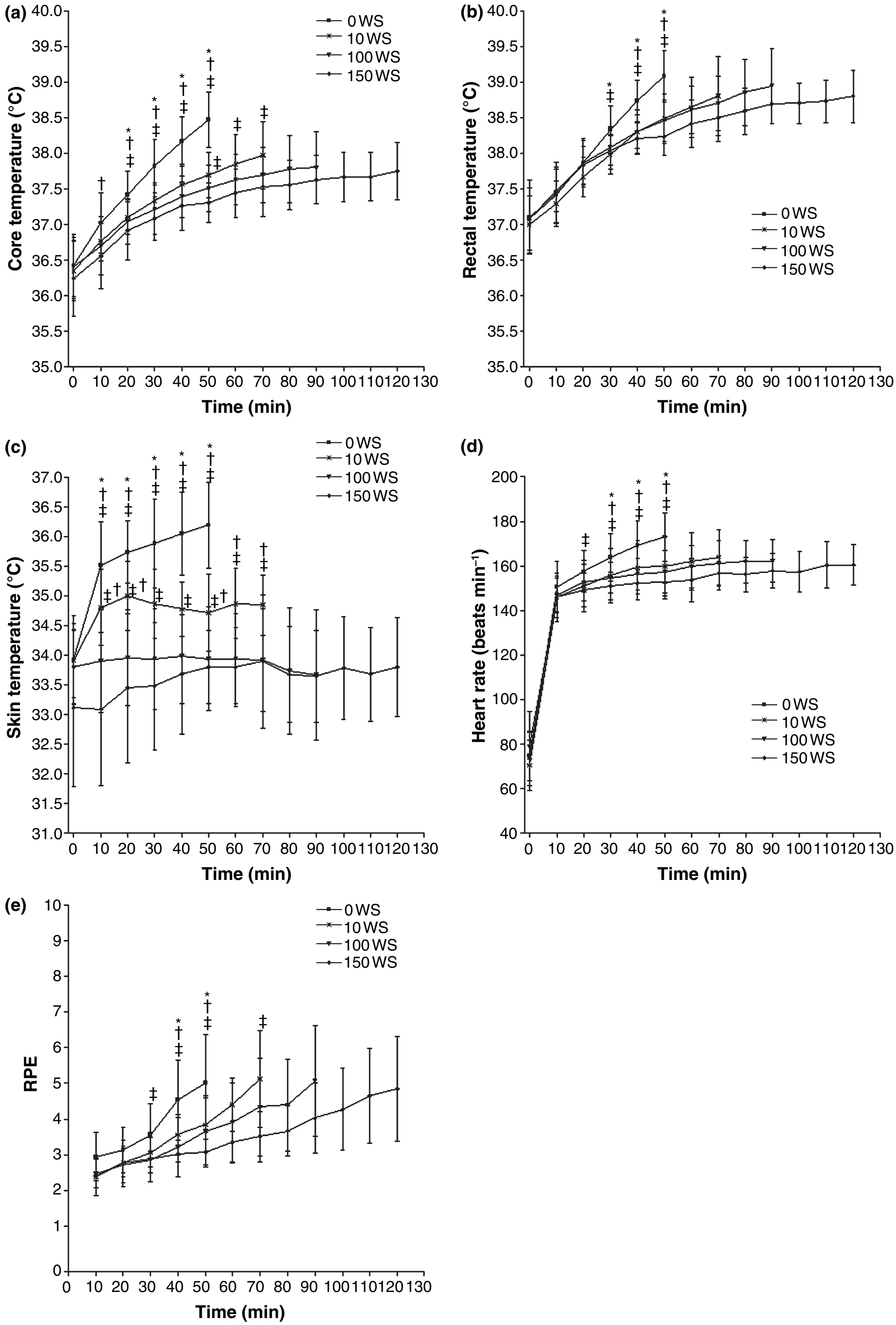

Figure 2 Calculated body temperatures (2a), rectal temperatures (2b), mean skin temperatures (2c), heart rates (2d) and RPE (2e) during trials with different air velocities. Values are mean values ± SD for nine subjects. *Significantly different from 10 WS ($P < 0.04$); †significantly different from 100 WS ($P < 0.01$); ‡significantly different from 150 WS ($P < 0.05$).

was calculated as 59.0 ± 7.3%, 57.8 ± 6.6%, 59.0 ± 5.6% and 60.7 ± 60.7% for 0, 10, 100 and 150 WS, respectively (Table 1). There was no significant difference in body weight loss per hour, fluid ingested per hour or sweat loss replacement between the different conditions, indicating that the preliminary trial to estimate sweat rate and fluid replacement requirements were successful in approximating 60% fluid replacement. However, sweat rate was significantly greater during 0 WS than during 10 and 150 WS ($P < 0.02$, Table 1), but was not significantly different between 10, 100 and 150 WS conditions (Table 1).

Manipulation of fluid intake during cycling with constant environmental conditions

The experiments in this section compared the effects of two different rates of fluid ingestion on thermal balance when the environmental conditions were kept constant and, in which an exercise specific air velocity equal to 100% of the calculated road-speed (100 WS) was studied.

Two subjects were unable to complete the high fluid ingestion condition for reasons unrelated to the experiment. Therefore, results are compared until 90 min. The removal or inclusion of their results, however, did not alter the findings. Comparison of the remaining results over 120 min also did not alter the findings.

Fluid replacement was 59.0 ± 5.6 and 80.0 ± 6.8% of calculated sweat rates during the low fluid intake (100 WS) and high fluid intake (100.80 WS) conditions, respectively ($P < 0.02$, Table 2). Fluid intake over the duration of the trial was significantly greater (1.70 ± 0.5 l vs. 2.17 ± 0.6 l, $P < 0.02$), and post-exercise body weight was significantly higher (70.5 ± 6.5 kg vs. 71.2 ± 6.8 kg, $P < 0.02$) in 100.80 WS. The percentage body weight loss was also significantly lower in the high fluid intake condition (100.80 WS) ($P < 0.02$, Table 2).

No significant difference was found in heat storage (Fig. 3 left panel) or sweat rate (Fig. 3 right panel) between the two conditions. Body temperatures (Fig. 4a) and rectal temperatures (Fig. 4b) followed the same pattern, both increasing similarly over time, and there were no differences between 100 WS and 100.80 WS at any time during the trial. Similarly, no significant differences were found in skin temperature (Fig. 4c), heart rate (Fig. 4d) or RPE (Fig. 4e) at any time during the trials.

Figure 5 shows the potential rates of heat loss through the different thermoregulatory mechanisms. This is calculated for the conditions in which the experiment was conducted using skin and ambient temperatures and humidities recorded in this study. The figure does not reflect the actual amount of heat lost by the different mechanisms, but rather the maximum rate at which heat could be lost in each of the trial conditions. The figure shows that whereas the rates of radiative and convective heat losses are largely independent of the facing windspeed at the ambient temperature used in the present study, evaporative heat loss increases as a more linear function of increasing windspeed.

Discussion

The first important finding of this study was that the environmental conditions in part 1 influenced the ability of the subjects to complete the 120 min of exercise although they drank fluid at the same rates (Table 1) during all four trials and hence were equally dehydrated at the moment of exercise termination (Table 1). Whereas no subject completed the 0 WS condition, eight completed the 100 WS and all nine completed the 150 WS condition. We conclude that the prevailing air velocity influences the ability of the athlete to perform a set amount of work whilst maintaining the rectal temperature below 40 °C when the rate of fluid intake is regulated at 60% of estimated sweat losses.

Accordingly, our second important finding was that the inability of the subjects to complete 120 min of exercise in the 0 WS condition was caused by an

Table 1 Pre- and post-exercise body weights (BW), body weight loss and fluid replacement in the four conditions

	0 WS	10 WS	100 WS	150 WS
Pre-BW (kg)	71.8 ± 6.7	71.8 ± 7.0	71.7 ± 6.5	71.9 ± 6.9
Post-BW (kg)	70.9 ± 0.8*	70.7 ± 6.8*	70.5 ± 6.5*	70.8 ± 6.7*
BW loss h^{-1} (%)	0.91 ± 0.3	0.87 ± 0.2	0.85 ± 0.2	0.76 ± 0.2
Sweat rate (l h^{-1})	1.61 ± 0.5†,‡	1.44 ± 0.4	1.47 ± 0.4	1.41 ± 0.3
Fluid intake (l h^{-1})	0.95 ± 0.3	0.88 ± 0.3	0.87 ± 0.2	0.86 ± 0.2
Sweat losses replaced (%)	59.0 ± 7.3	57.8 ± 6.6	59.0 ± 5.6	60.7 ± 7.2

Values are mean values ± SD for nine subjects.
*Significantly different from pre-BW ($P < 0.00006$); †significantly different from 10 WS ($P < 0.02$); ‡significantly different from 150 WS ($P < 0.003$).

Table 2 Pre- and post-exercise body weights (BW), % BW loss, fluid intake and % sweat losses replaced in the 100 and 100.80 WS conditions

	100 WS	100.80 WS
Pre-BW (kg)	71.7 ± 6.5	71.7 ± 6.9
Post-BW (kg)	70.5 ± 6.5*	71.2 ± 6.8*,†
BW loss (%)	1.7 ± 0.5	0.7 ± 0.3†
Fluid intake (L)	1.7 ± 0.5	2.2 ± 0.6†
Sweat replacement (%)	59.0 ± 5.6	80.0 ± 6.8†

Values are mean values ± SD for nine subjects.
*Significantly different from pre-BW ($P < 0.00005$);
†significantly different from 100 WS ($P < 0.02$).

increased rate of heat storage due to a failure of heat transfer to the environment which was independent of any failure of sweating. Indeed, rates of sweat loss were highest in the 0 WS condition (Table 1) indicating that the limitation for heat transfer existed not in the thermoregulatory capacity of the exercising humans, but in the ability of the environment to absorb and dissipate that heat.

The potential for heat loss was, therefore, greatly increased in the 10 WS condition compared with 0 WS largely because of the increased potential for evaporative heat loss (Fig. 5 right panel) although sweat losses were lower (Table 1). This was shown by the significantly lower values for heat storage (Fig. 1a), body temperature (Fig. 2a), rectal temperature (Fig. 2b), skin temperature (Fig. 2c) and the longer exercise duration despite the significantly lower sweat rate (Table 1). The slightly decreased skin-environment temperature gradient caused by the decreased skin temperature is compensated for by an increase in evaporative heat loss, resulting in reduced heat storage.

Accordingly, we conclude that in windstill conditions or at very low wind speeds, excessive heat storage occurs in the human exercising at a moderate to high intensity, not as a consequence of human thermoregulatory failure but because of a reduced capacity of the environment to absorb the heat generated by such vigorous exercise. This finding has important implications for the interpretation of those studies of human exercise in which high environmental heat loads are imposed without the provision of conditions that afford the opportunity for adequate convective cooling. Indeed this is not a novel finding.

Thus, Adams *et al.* (1992) compared thermoregulatory responses to cycling at 52% VO_{2max} at 24 and 35 °C, with circulating air velocities of <0.2 m s^{-1} (0.75 km h^{-1}) and 3 m s^{-1} (11.25 km h^{-1}). Oesophageal temperatures were significantly higher in the 35 °C condition with the low air velocity (38.82 ± 0.30 °C vs. 37.78 ± 0.16 °C; low wind vs. modest wind; $P < 0.05$); heart rates were also lower in the modest wind condition. Similarly, Shaffrath & Adams (1984) studied cyclists exercising at 60% VO_{2max} at 24 °C and 39.5% RH with circulating air velocities of <0.2 m s^{-1} (0.75 km h^{-1}) or 4.3 m s^{-1} (15.5 km h^{-1}). Rectal ($P < 0.002$) and skin temperatures ($P < 0.0001$) were again significantly lower in the conditions of modest air velocity. Sweat rates in both these studies were also significantly higher in the low wind conditions, as also reported here (Table 1).

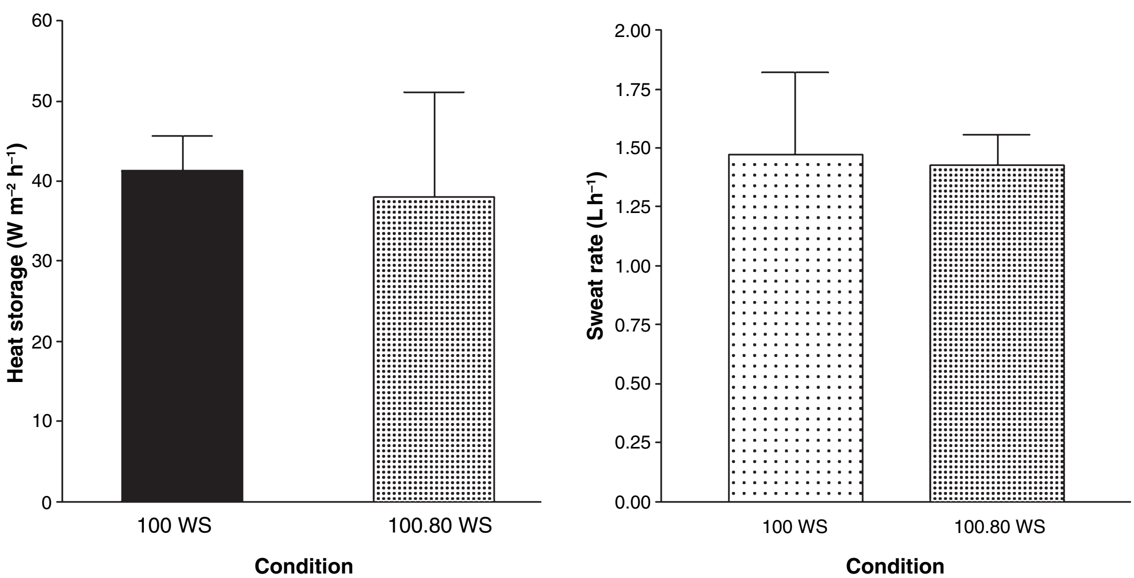

Figure 3 Calculated heat storage (left panel) and estimated sweat rates during trials with different ingested fluid volumes. 100 WS = 60% of measured weight losses replaced; 100.80 WS = 80% of measured weight losses replaced. Values are mean values ± SD for nine subjects.

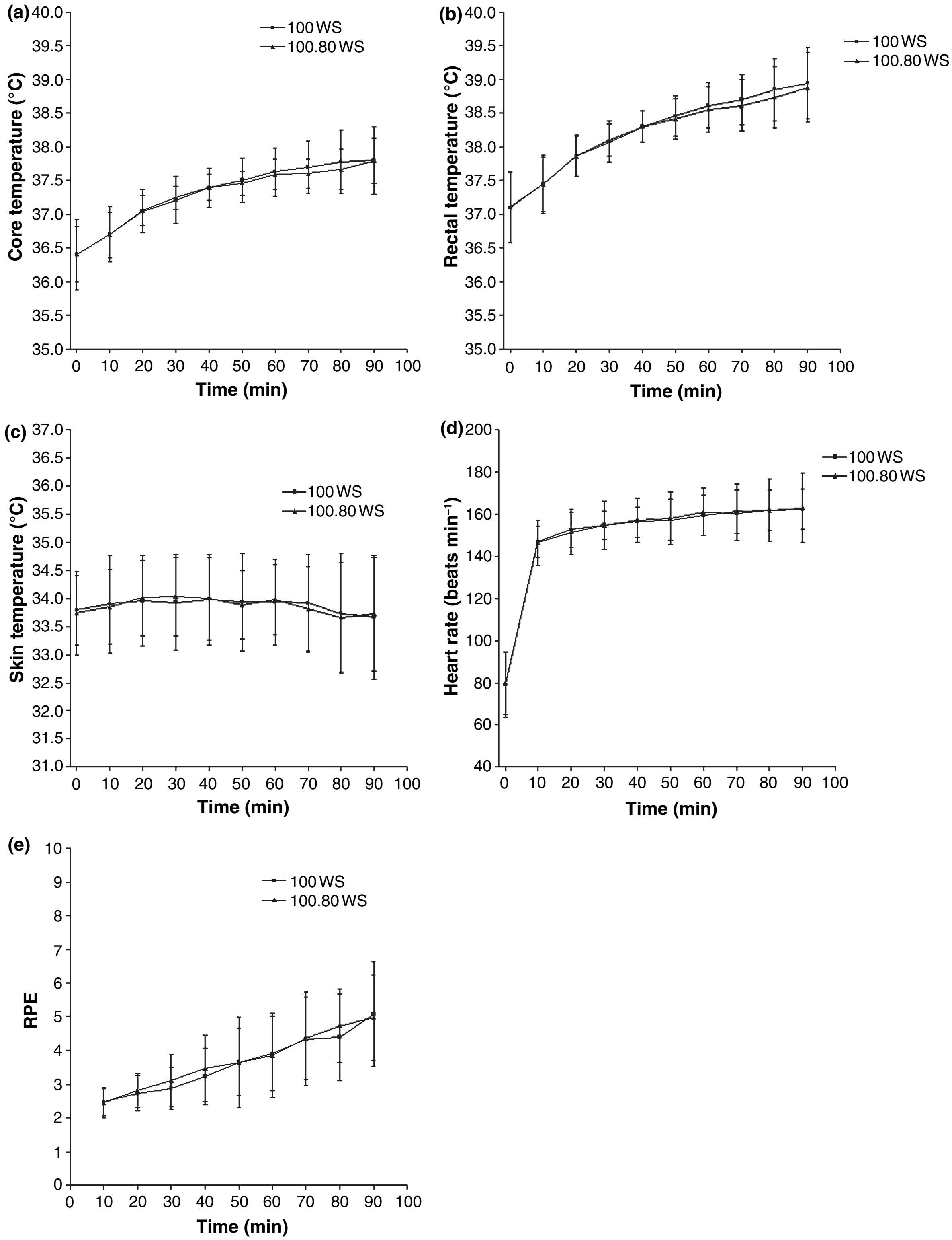

Figure 4 Calculated body temperatures (4a), rectal temperatures (4b), mean skin temperatures (4c), heart rates (4d) and RPE (5e) during trials with different ingested fluid volumes. Values are mean values ± SD for nine subjects.

Sweating can be initiated by central stimulation before there is a rise in body temperature (Ogawa & Sugenoya 1993), but is also influenced by the amount of mechanical work being performed and by humoral factors activated by exercise (Ogawa & Sugenoya 1993). An increase in central brain temperature can

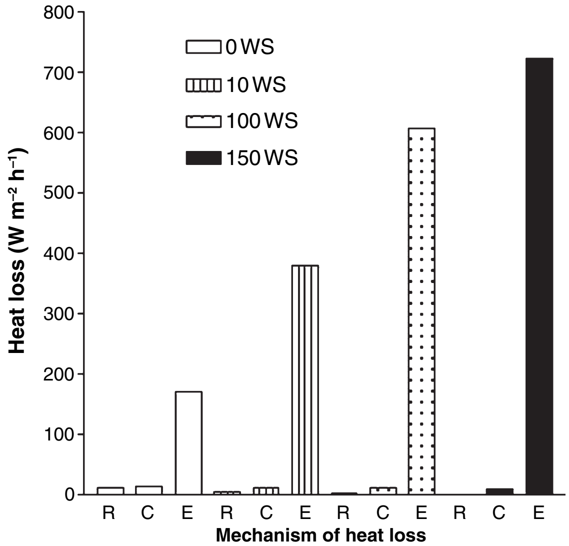

Figure 5 Calculated potential heat loss by means of radiation (R), convection (C) and evaporation (E) for different windspeeds.

also stimulate the thermoregulatory mechanisms independently (Holdcroft 1980). With the exception of the core and skin temperatures, each of these factors was likely constant in these trials since cyclists maintained the same workload in all trials.

Therefore, the increase in sweat rate in the 0 WS condition may be due to the significantly increased skin temperature (Robinson *et al.* 1950), which acts as a local stimulus for the sweating response (Ogawa 1970), and also to the significantly increased body temperature in 0 WS. The raised skin temperature is the result of decreased evaporative cooling of the skin and a consequently increased peripheral vasodilation associated with the increased skin temperature (Shaffrath & Adams 1984).

Our third important finding was the progressively although smaller increases in heat storage as the windspeed increased to the 150 WS condition, so that heat storage was significantly less in the 150 WS condition that in the 10 WS condition. Indeed, Figure 1 shows that heat storage fell as a non-linear function of windspeed. This indicates that at some windspeed, the thermoregulatory capacity of the body rather than that of the environment limits thermal balance since the heat dissipating capacity of the environment can continue to increase with increasing air velocity.

Accordingly, we conclude that this study shows that the environmental conditions might falsely influence the interpretation of studies performed especially in hot, humid conditions with a low circulating air velocity. Therefore, in the 0 and 10 WS conditions in this study, the rate of sweating far exceeded the evaporative capacity of the environment, causing an excessive sweat rate and heat retention. However, at the higher air velocities (100 and 150 WS) the body was able more accurately to match rates of heat loss and heat production since the evaporative capacity of the environment equalled or exceeded the maximum sweat rate achieved during exercise in those environmental conditions. Thus, any intervention that influences heat balance during exercise, for example mild to severe dehydration, might be physiologically important only under those artificial laboratory conditions in which more vigorous or prolonged exercise is undertaken without an appropriate windspeed to allow adequate convective cooling. Indeed, many highly influential laboratory studies that have fashioned current opinions of the dangers of dehydration or conversely the value of fluid ingestion during exercise have been performed in hot and humid environmental conditions in which subjects were exposed to inappropriately low circulating air currents based on the intensity of exercise being performed.

Pitts *et al.* (1944) studied men marching in the heat (37 °C, with 30 or 83% RH), in windstill conditions. They found that subjects were able to march for longer, feeling fresher and with a lower rectal temperature when ingesting water at rates equivalent to rates of sweat loss compared with either no water or water *ad libitum*. However, differences between full fluid replacement and water *ad libitum* were small and occurred only after 5 h of marching. Barr *et al.* (1991) examined subjects while cycling for 6 h in hot conditions (30 °C; 50% RH) ingesting either a volume of water equal to weight loss, or an equivalent volume of NaCl solution, or nothing. They did not report any air velocities. The results showed that rectal temperature was higher in the no fluid condition than in the other two conditions, but only after the third hour of exercise ($P < 0.001$). The ability to complete the trial within the physiological limits (95% HR_{max}, $T_{rec} = 40$ °C) was improved by the ingestion of either water or a sodium chloride solution.

Similarly, Gisolfi & Copping (1974) examined athletes running for 1.5–2.5 h at 75% VO_{2max} in hot conditions (33.5 °C; 38% RH) whilst ingesting either warm water, cold water or nothing. Although subjects ran at between 12.8 and 14.4 km h^{-1}, the air velocity was so low as to be negligible (2.2 km h^{-1}). Subjects who did not ingest fluid developed higher rectal temperatures but only after 90 min of exercise. Based on our findings (Figs 2 and 3), we speculate that this difference in rectal temperatures may have been attenuated with the provision of an appropriate air velocity corresponding to the running speeds utilized in the study.

Costill *et al.* (1970) also examined subjects who ran at 70% VO_{2max} for 2 h in moderate conditions (24.8–25.6 °C; 49–55% RH) whilst ingesting either water or a carbohydrate-salt (CHO-SALT) solution every 20 min, or nothing (NF). The air velocity during the trials was only 5.7 km h^{-1}. Only after 70 min were rectal temperatures higher when athletes did not ingest fluid, so that terminal rectal temperatures at 120 min were the following: NF 39.4 ± 0.9 °C; water 38.7 ± 0.7 °C; CHO-SALT 38.6 ± 0.8 °C. The authors also noted that in all three conditions 'the runners' skin was sufficiently wetted by sweating to permit maximal evaporation'. Indeed, the sweat rates did not differ between conditions (NF 1.51 ± 0.2 l h^{-1}; water 1.55 ± 0.1 l h^{-1}; CHO-SALT 1.65 ± 0.2 l h^{-1}).

But, according to our findings, these results fail to show any impaired thermoregulatory capacity – for example, a reduced sweat rate – with dehydration, but rather an increase in heat gain, due to inadequate evaporative cooling as shown by the comparison of the 0 and 10 WS conditions in this study (Fig. 1). Indeed, many studies using continuous exercise have failed to show that dehydration reduces the sweat rate during exercise (Costill *et al.* 1970, Gollnick *et al.* 1972, Fortney *et al.* 1981, Nielsen *et al.* 1984, Armstrong & Maresh 1998, Coyle 1998, Cheuvront & Haymes 2001). Only in studies in which subjects begin exercise in a dehydrated state (Fortney *et al.* 1981, Buono & Wall 2000) or are involved in intermittent exercise (Pearcy *et al.* 1956, Senay 1968) is sweat rate decreased with dehydration. Indeed, Costill *et al.* (1970) concluded that fluid ingestion reduced the rectal temperature during exercise not as the result of superior thermoregulation but as a consequence of the cooling effect of the cold fluid that was ingested.

An important point is that during running, the resulting air velocity is lower than during cycling. The high air velocities used in this study in the 100 WS and 150 WS conditions, while appropriate for cycling, would represent an artificially elevated air velocity for out of doors running exercise, and so the results of the present study should be applied to running with caution, since the reduced air velocities would result in a reduced capacity for convective and evaporative heat loss. However, it should be noted that those laboratory studies of running have used wind velocities that are substantially lower than expected during out of doors exercise. For example, Gisolfi & Copping (1974) and Costill *et al.* (1970) utilized air velocities lower than 5.7 km h^{-1} despite running speeds between 12 and 14.4 km h^{-1}. We speculate that the differences in body temperatures measured in these studies might have been delayed or attenuated in the presence of appropriate air velocities.

Another study that is used to support current drinking guidelines during exercise (Convertino *et al.* 1996) investigated the effects of graded dehydration on thermoregulatory function in conditions similar to that of this study. Subjects cycled for 2 h in hot conditions (33 °C; 50% RH) at 62–67% VO_{2max}, equivalent to an average power output of 206 ± 14 W (Montain & Coyle 1992a). Graded dehydration had a graded effect on the heat retention during exercise. This study was also performed with an air velocity of only 8.6 km h^{-1} compared with a predicted cycling velocity of 35.6 km h^{-1} at the power output in out-of-doors competition according to the equation of Di Prampero *et al.* (1979). The difference in rectal temperature between the highest rate of fluid ingestion (2380 ± 93 mL in 2 h, 1190 mL h^{-1}) and moderate fluid ingestion (1423 ± 48 mL, 711.5 mL h^{-1}) was only 0.2 °C (38.4 ± 0.1 vs. 38.6 ± 0.1 °C), substantially less that the effects of increasing air velocity (~1 °C – Figs 2 and 3) measured in this study.

Indeed the second part of this study specifically addressed the finding of Montain & Coyle (1992b) that higher rates of fluid ingestion improve, albeit to a relatively minor degree, thermoregulation during exercise in hot, humid conditions when the facing air velocity is low and less than 25% of the velocity that cyclists would experience in out-of-doors exercise. By studying moderate (0.85 ± 0.2 L h^{-1}, 59 ± 5.6% sweat replacement) and high (1.1 ± 0.3 L h^{-1}, 80 ± 6.8% sweat replacement) rates of fluid ingestion during exercise undertaken in the identical environmental conditions but with an appropriate air velocity (100% of calculated road speed), we found that higher rates of fluid ingestion did not influence heat storage (Fig. 3), body temperature (Fig. 4a), rectal temperature (Fig. 4b), or skin temperature (Fig. 4c). This finding illustrates that in conditions of high evaporative capacity of the environment, moderate (1.7%) dehydration during exercise does not adversely affect thermoregulation. This contrasts with the conclusions of previous investigators (Pitts *et al.* 1944, Ekblom *et al.* 1970, Armstrong *et al.* 1985, Sawka *et al.* 1985, 1996, 1998, Sawka 1992, Galloway & Maughan 1997). In particular, Montain & Coyle (1992b) found that a 33% difference in ingested fluid volume during cycling resulted in a 1.2% difference in change in body weight. This was associated with a significantly increased rectal temperature after 100 min of exercise. In our study, the 20% difference in fluid intake between 100 and 100.80 WS resulted in a 1% difference in change in body weight (0.7% in 100 WS vs. 1.7% in 100.80 WS), yet the rectal temperature and body temperature did not differ at any stage during the trials (Fig. 4a, b). This is in contrast with the current ACSM position stand on exercise and fluid replacement (Convertino *et al.* 1996), which states that 'even a small amount (1% body weight) can increase cardiovascular strain as indicated by a disproportionate elevation of heart rate during exercise, and limit the ability of the body to transfer heat from contracting muscles to the skin surface where heat can be dissipated to the environment'. The discrepancy can be explained by the difference in environments between previous studies and the current one; specifically, experiments in environments in which the ability of the environment to absorb heat from the body is diminished due to the unnaturally low facing windspeed (Buono & Wall 2000).

Given our finding that the capacity to thermoregulate in the heat is limited by the environment in windstill conditions, it follows that these studies (Montain & Coyle 1992b, Convertino *et al.* 1996) may have overestimated the real influence of dehydration on the measured physiological changes and the impaired exercise performance, and may have underestimated the detrimental effect of the windstill conditions. Furthermore, it is possible that the use of specific environmental conditions of low air velocity may have resulted in an underestimation of the human's ability to adapt to the dehydration that develops during exercise. Indeed, all the classical laboratory studies (Costill *et al.* 1970, Montain & Coyle 1992b, Armstrong & Maresh 1998) that have evaluated the effects of dehydration caused by the absence of drinking during exercise, and which are most usually quoted as evidence for the importance of fluid ingestion during exercise (Convertino *et al.* 1996) were all completed in conditions of unnaturally low air velocities. Rather, our findings support the conclusion that none of these studies proves that mild dehydration impairs the normal thermoregulatory functions of the body. Rather, the findings may be an artefact of the unnaturally low evaporative capacity of the chosen environmental conditions.

It is, however, necessary also to note that the temperature of the moving air will affect heat storage. Whereas a cooler wind will increase both the evaporative and convective heat losses by increasing the convective heat loss gradient and the wind chill factor, moving air with a temperature that approximates that of the skin will result in no or little convective heat loss so that any additional heat loss will have to come from evaporation. In still hotter conditions, moving air will result in heat gain via convection; thus the heat loss via evaporation must first offset this heat gain before resulting in a net heat loss (Dennis & Noakes 1999).

Therefore, it is arguable that in the studies performed in hot conditions (Ladell 1955, Pearcy *et al.* 1956, Senay 1968, Gisolfi & Copping 1974, Montain & Coyle 1992b) an increased air velocity may have resulted in extra heat gain. However, given the high latent heat of sweat evaporation of approximately 680 W h L^{-1} (Kenney 1998), it is unlikely that the convective heat gain would exceed or even equal evaporative heat loss (Pitts *et al.* 1944, Wenger 1972). Therefore, an increased air velocity even in those experiments would still have resulted in increased heat loss from the body.

In the conditions of this study, the ability of the environment to absorb heat from the body is substantially increased due to the much higher air velocity ($\sim$33 km h^{-1}). Therefore, any increase in body temperature in those conditions could be attributed exclusively to the thermoregulatory failure of the body due to dehydration since the environmental conditions no longer limited heat loss. Since no difference in thermoregulatory capacity was found, we conclude that the body can dehydrate to 1.7% without any detrimental effects on heat storage. This is equal to a body weight loss of 1.2 kg for a 70 kg man over a 2-h exercise period.

Indeed, this concept that the body has a store of extra water at rest available for sweat loss and other bodily functions in case of need, such as exercise, was first proposed by Ladell (1955). He found a linear correlation between the level of dehydration and the increase in rectal temperature only once 2.5 kg of weight have been lost. Interestingly, Wyndham & Strydom (1969) also found that there was a 3% threshold dehydration level, only above which was there a linear relationship between the increase in rectal temperature and percentage dehydration during exercise. This relationship implies that dehydration only begins to affect the thermoregulatory mechanisms once the body has dehydrated beyond a certain point. This threshold level may be different among individuals (Senay 1968), resulting in confounding results between studies. While studies have attempted to disprove this relationship (Pitts *et al.* 1944, Pearcy *et al.* 1956, Senay 1968, Ekblom *et al.* 1970, Gisolfi & Copping 1974, Myhre *et al.* 1979, Nadel *et al.* 1979, Barr *et al.* 1991, Nicol *et al.* 1991, Montain & Coyle 1992a,b, Ross & Marfell-Jones 1992), they have performed the experiments in conditions in which the ability of the environment to absorb heat limits the body's thermoregulatory capacity. Therefore, the application of these results to out-of-doors exercise is limited.

In summary, in warm, humid conditions of low air velocity, the ability of the body to lose heat is limited by the evaporative capacity of the environment. As a result, the body stores excess heat and the rectal temperature rises. At higher air velocities, the evaporative capacity of the environment is increased so that excess heat is dissipated and the extent of heat storage is reduced. Under these conditions, a higher rate of fluid ingestion has no influence on heat storage, body temperature, sweat rate, heart rate or RPE when air velocity is 33 km h^{-1} or higher.

Furthermore, laboratory studies of cycling and running employing wind speeds that are substantially lower than an athlete's estimated cycling or running speed (Costill *et al.* 1970, Gisolfi & Copping 1974, Montain

& Coyle 1992b) should not be used as a basis for the current fluid replacement guidelines (Convertino *et al.* 1996), since they underestimate the body's ability to adapt to mild dehydration and overestimate the beneficial effects of high rates of fluid ingestion.

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