Chapter 6

Appropriately trained humans can safely perform vigorous, competitive self-paced exercise in extreme heat (44°C) when drinking water *ad libitum*

6.1 Introduction

The goal of the American College of Sports Medicine (ACSM) Position Stands on fluids and exercise [2,7] is to insure that humans drink adequately and do not exercise in inappropriately hot conditions. The guidelines to establish safe environmental conditions for exercise are based in part on the concept of a thermal prescriptive zone [27,40,44,10,20] in which humans exercising at an externally-regulated (fixed) work rate (exercise intensity) are only able to reach thermal equilibrium at an increasingly higher level of core temperature [27] or unable to reach such equilibrium at all. Instead, continuing to exercise at that fixed work rate produces a progressive heat accumulation leading to an elevated brain temperature causing central fatigue [52] or "heat illness" including heat stroke.

Thus Eichna et al. [10] concluded that: "At wet bulb temperatures exceeding 94°F (34.4°C), most men are incapable of sustained effort; those who work do so inefficiently and ineffectively. A high incidence of heat casualties (often severe) is to be expected…clothing probably lowers the environmental upper limits" (p.82).

Those studies have encouraged the concept that humans have a limited capacity to prevent any of these outcomes if they exercise in extremely hot conditions, particularly if they fail to ingest fluid at rates to prevent either no [1] or a minimal body mass (BM) loss (<2% BM) during exercise. Thus human athletes exercising in the heat are sometimes considered to live on the edge of thermoregulatory catastrophe.[19,20]

Yet there are isolated reports of unusual human athletic performances in extreme heat. A feature of all these examples is that the participating athletes were able freely to modify their exercising work rate intensities in response to the prevailing environmental conditions. For example Karoha Langwane, the !xo San Bushman hunter was followed as he hunted for 4-6 hours in the Kalahari Desert, South Africa in an air temperature of 40-46°C covering in excess of 30km in loose sand while he drank only about 1L of water.[12] Similarly the woman's 42km marathon footrace at the 2000 Olympic Games was won by a 40kg Japanese athlete who ran 2:23:14 in conditions reported to be 35°C with relative humidity of 55%. This performance was only 3 minutes (~2.4%) slower than her personal best time run in much cooler conditions.

As part of a series of experiments to determine the minimal fluid requirements of soldiers during route marches [37,39], we were granted the opportunity to study a group of 18 exceptionally well conditioned and heat-adapted members of the South African Special Forces. The soldiers participated in an individually-timed, competitive 25km route march in a dry bulb temperature that reached 44.3°C (mean WBGT index of 30°C; maximum value of 31.3°C). The soldiers were inappropriately dressed for the activity since they wore full combat dress which covered their arms and legs. Furthermore each carried a rifle and a combat backpack (weighing 26 kg). During the march soldiers had free access to all the water they required.

While the data collection in this study is descriptive and do not address any specific hypothesis, we believe they may represent a unique testimony to the remarkable physiological capacity of some appropriately-trained humans to safely sustain high rates of energy expenditure for prolonged periods in extreme heat even when heavily burdened and inappropriately attired.

Furthermore this data is compatible with the theory that a critical determinant of the direction of human evolution was the development of a superior thermoregulatory capacity that allowed hominids to successfully perform persistence hunts of non-sweating mammals in extreme dry heat on the African savannah beginning about 2 million years ago.[26,15] They also indicate that the biological controls that likely evolved in that process appear to be sufficient to maintain whole body homeostasis in subjects who drink only according to the dictates of thirst (*ad libitum*) and who are able to modify their exercise intensities according to the prevailing environmental conditions.

6.2   Methods

Subject Selection

Ethical clearance for this study was obtained from 1 Military Hospital Research Ethics Committee within the South African Military Health Services (SAMHS) of the South African National Defence Force (SANDF). Eighteen subjects volunteered for this study. All were experienced and conditioned to route marches with payloads of up to 35 kg, medically fit to participate in the study and without any musculoskeletal injuries. Subjects were told that they could terminate

their participation at any stage without any consequences to their careers. All were required voluntarily to sign an informed consent form before they were accepted for participation in the study. The subjects were asked to provide basic demographic information for record purposes. Two days prior to the route march, the sub-maximal oxygen consumption of each subject was directly measured using a MetaMax™ portable gas analyser (Cortex Biophysik, Germany) during the Harvard graded step-up test. Their predicted aerobic capacity was calculated from the sub-maximal exercise test results and the resulting individual regression equation for heart rate versus oxygen consumption at different workloads according to the method described in ISO 8996.

Exercise intervention

During the route march of 25 km each participant carried a mass of 26 kg which included their backpack, rifle, and water supply during the march. All backpacks were packed in a similar configuration and weighed prior to the start of the exercise. Water was the only fluid allowed during the march and was available for replenishment if required at frequent intervals during the exercise. Soldiers were instructed to drink *ad libitum* during the march. Their core body temperatures were continuously measured at one minute intervals with a CorTemp ™2000 ambulatory remote sensing system (HQ Inc, USA). Core temperature data were evaluated for the potential confounding effect of fluid ingestion invalidating the ingestible sensor.[25,50] The wet bulb globe temperature (WBGT) index, temperature and relative humidity were monitored for the duration of the exercise (Davis Health

Environmental Monitor and Questemp, Quest Technologies, South Africa).

Hydration markers

Prior to the exercise intervention each subject emptied his bladder and provided a saliva sample for analysis of deuterium abundance. Saliva was chosen due to the ease and non-invasive nature of its collection, as well as the fact that saliva has been proven as a valid and convenient sampling medium for determining TBW through the diluted isotope technique.[14,45,51] Furthermore it has been documented that enrichments of deuterium oxide in saliva and plasma samples were identical and reached a 2 hour plateau after administration of an oral dose of the tracer.[74] Determining TBW through the diluted isotope technique remains the most reliable method currently available, producing lower coefficient of variation values than methods such a bioelectrical impedance.[45]

A pre-exercise blood sample (5 ml) was collected from the antecubital vein to determine serum sodium concentration $[Na^+]$ and plasma osmolality. Samples were collected after the subjects had been seated for 45 minutes.

Subjects were weighed wearing only their underclothing (to the nearest 0.02 kg). As previously described (38), individual deuterium oxide doses (± 0.05 g/kg body mass) were pre-mixed from 99% deuterium oxide (made up as a 4% weight-to-weight solution with water). Appropriate weighing of the dose bottle (to the nearest 0.1g) was

performed in order to determine the exact dose consumed by each participant. After a two hour equilibration period [9,48] a second saliva sample was collected in order to determine the pre-exercise total body water (TBW).

The exercise intervention followed, at the completion of which each participant was provided with a towel to dry excess perspiration prior to re-weighing. A third saliva sample were collected and used for the determination of post-exercise deuterium abundance. This value was used as the new deuterium abundance baseline post-exercise. The participants then received their post-exercise deuterium oxide dose followed by a two hour equilibration period.

Participants also received a post-exercise dose of oxygen-18 in order to perform a concurrent measure of TBW with an additional tracer to ensure that the second (post-exercise) deuterium oxide dose did not overestimate the TBW.

No food or fluids were allowed during any of the two 2-hour equilibration periods. To avoid contamination of the saliva, care was also taken to ensure that no food or fluids were ingested for at least 45 minutes prior to any of the saliva sampling. Urine voided during this period was recorded for correction of isotope loss.

A post-exercise blood sample was also collected 45 minutes after completion of the march. This period ensured that metabolic rates were closer to that of the pre-exercise level and allows for the majority of fluid

loss through post-exercise sweating to have ceased. This period also allowed for the return of exercise-induced plasma volume shifts to pre-exercise levels. Samples were drawn from subjects while seated as for the pre-exercise sample.

A final saliva sample was collected and body mass measurement performed in order to calculate post-exercise TBW. The samples were analysed by continuous flow isotope ratio mass spectrometry using a Europa Scientific ANCA-GSL and Geo 20-20 isotope ratio mass spectrometer. TBW, which is comprised of extracellular fluid (ECF) and intracellular fluid (ICF), averages approximately 60% of body mass. However due to the influence of body composition, specifically individual variances in fat free mass, the range has been reported from approximately 45 to 75 percent [45] of TBW. Total body water (kg) was calculated using the preferred method of Halliday and Miller [14] according to the following equation:

TBW (Kg) = ((((T*A)/a)*((Ea-Et)/(Es-Ep)))/1000) / 1.04, in which

A = amount of dose solution drunk (grams)

a = amount of dose solution diluted in T (grams)

T = amount of tap water 'a' was diluted in

Ea = enrichment of diluted dose

Et = enrichment of tap water used to dilute the dose

Ep = enrichment of baseline sample.

Es = enrichment of post dose sample

1.04 = correction factor for over estimation due to exchange with non-aqueous hydrogen.

Diluted isotope methods designed to measure TBW at the time of isotope administration are subject to systematic errors from water entering the body between the time of dosing and the sample collection.[45] Corrections were made for the ingestion of the isotope dose, metabolic water production and water added to the TBW pool through exchange with atmospheric moisture according to the methods of Schoeller et al.[45] Since most of the correction factors are depended on metabolic rate, additional corrections were made for the post-exercise equilibration period during which an increased metabolic rate (excess post exercise oxygen consumption (EPOC), although marginal [13,3] would augment the over-estimation through increased metabolic water production.

The sweat losses during the march were calculated according to methods previously described by Rogers et al.[42] Respiratory water loss was calculated by the methods of Mitchell et al.[29] For all calculations and estimations involving respiratory exchange ratio (RER) and oxygen consumption (VO_2), we assumed that the RER averaged 0.85 and that the oxygen consumption approximated 65% of the VO_{2max} throughout the exercise [8,34,42]. Even if the actual RER and VO_2 of the participants differed slightly from these assumptions, the outcomes would not have been greatly different.

Statistical analyses

In order to determine which statistical test would be most suited for the comparisons of pre- and post-exercise values, the differences (paired differences) between the pre- and post-exercise results were calculated. The distributions (in the form of histograms) of paired differences of all the results were plotted with the number of classes as calculated according to the Rule of Sturge. The normality of this distribution was tested by means of the Shapiro-Wilks' W test. The statistical Rule of Sturge states that the number of classes equals N x 1.4 + 1 (where: N = sample size). Student's T-tests were used to compare results where the distribution of the paired differences was normal. Where the distribution of the paired differences was not normal, the non-parametric alternative to the student's T-test, the Wilcoxon Rank Sum Test was used to compare results. A Pearson's product moment correlation coefficient was used to determine relationships between appropriate variables. Statistical significant differences were indicated by a p-value of less than 0.05. The statistical analyses were completed using the STATISTICA© software package.

6.3 Results

Eighteen male subjects with an average age of 26 years (range of 21-38 years) volunteered for the study. The subjects had an average stature of 175 cm (165-190 cm). Their mean predicted VO_{2max} was 55 ml/kg/min (40-65 ml/kg/min). On average the subjects carried a pay load mass of 26 kg each. The mean WBGT during the route march was 28.8 °C (26.9-31.3°C). The mean relative humidity was 16.8% (15-

28%) while the mean dry bulb temperature was 40.2 °C (34.9-44.3°C). The mean time to complete the route march was 4h17min with a range of 3h57min to 4h47min.

Body mass loss, fluid intake and sweat rates

On average the group lost 2.73 kg (3.8%) ($p<0.05$) during the exercise with a range of 1.5 kg to 4.7 kg (2-6%) (Table 1). The group consumed on average 1264 ml/hr during the exercise. The subject with the largest intake consumed 1782 ml/hr while the subject with the smallest intake consumed 999 ml/hr (Table 1). There was no significant relationship ($p>0.05$) between body mass loss (%) ($r = 0.57$) or amount of fluid consumed ($r = 0.10$) and peak exercise core temperature during exercise (Figures 1 and 2).

Table 1: Body mass change, water intake, sweat rates, plasma osmolality and serum [Na^+] during a 25km march.

|	Minimum	Mean (±SD)	Maximum
Body mass (pre-exercise) [kg]	59.7	72.9 (8.0)	89.2
Body mass (post-exercise) [kg]	57.9	70.1 (8.0)	87.0
Body mass loss [kg]	-1.52	-2.73 (0.98)	-4.74
Body mass loss [%]	-2.0	-3.8 (1.4)	-6.2
Total water intake [ml]	4199	5410 (831)	7101
Water intake [ml/hr]	999	1264 (229)	1782
Sweat rates [ml/hr]	1449	1789 (267)	2191
POsm (pre-exercise) [mosm/kg]	294.0	300.6 (4.5)	312.0
POsm (post-exercise) [mosm/kg]	291.0	303.6 (5.8)	311.0
[Na^+] (pre-exercise) [mmol/kg]	140.0	143.3 (2.0)	147.0
[Na^+] (post-exercise) [mmol/kg]	140.0	144.0 (2.5)	148.0
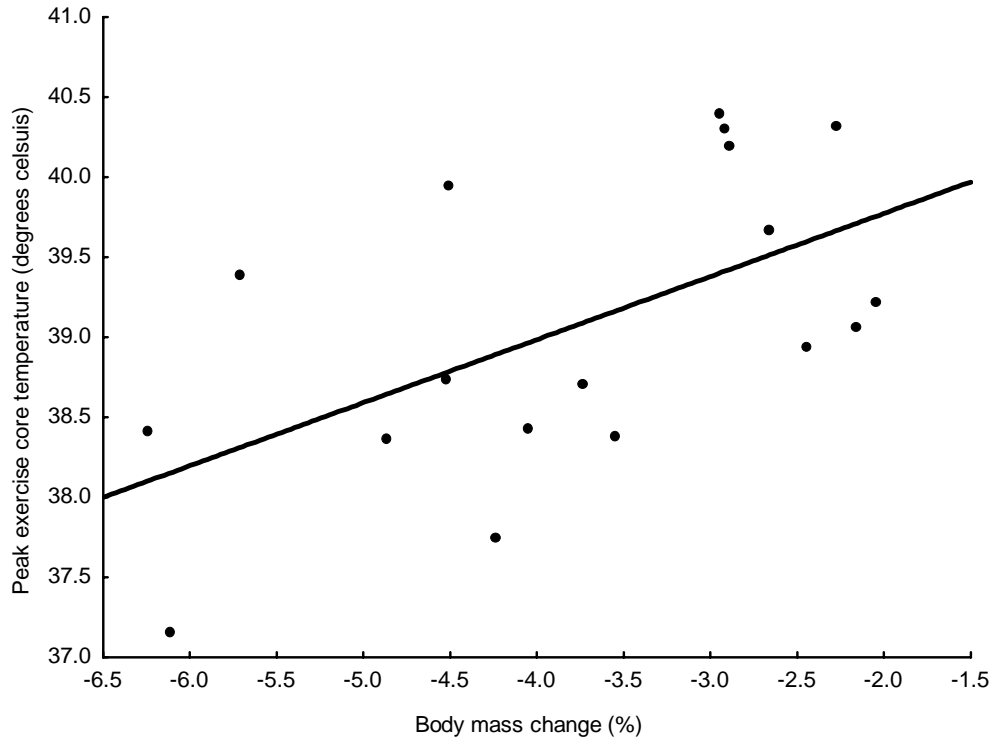
**Figure 1:** The relationship between changes in body mass and peak exercise core temperature (p>0.05, r = 0.57).
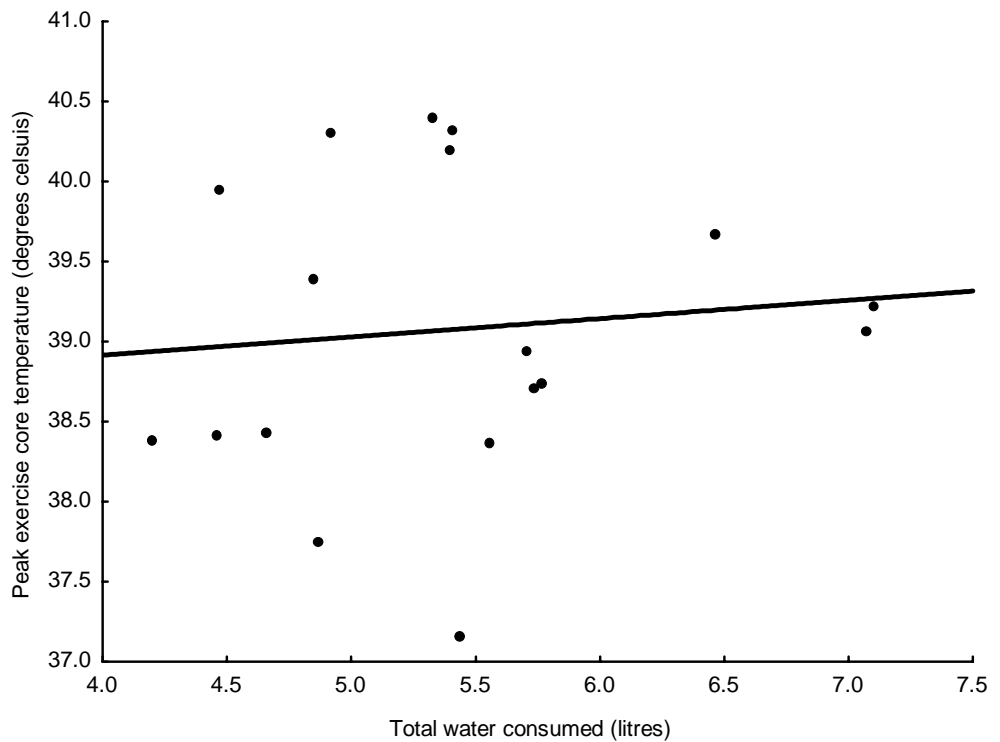
Figure 2: The relationship between fluid consumption and peak exercise core temperature (p>0.05, r = 0.10).

Plasma osmolality (POsm) and serum [Na⁺]

POsm and serum [Na⁺] values pre- and post-exercise are also listed in Table 1. Neither POsm nor serum [Na⁺] changed significantly during exercise. There was a significant relationship ($r = -0.76$) between post-exercise serum [Na⁺] and body mass change (kg) during exercise (Figure 3) and a significant relationship ($r = -0.73$) between post-exercise serum [Na⁺] and change in TBW (kg) (Figure 4).
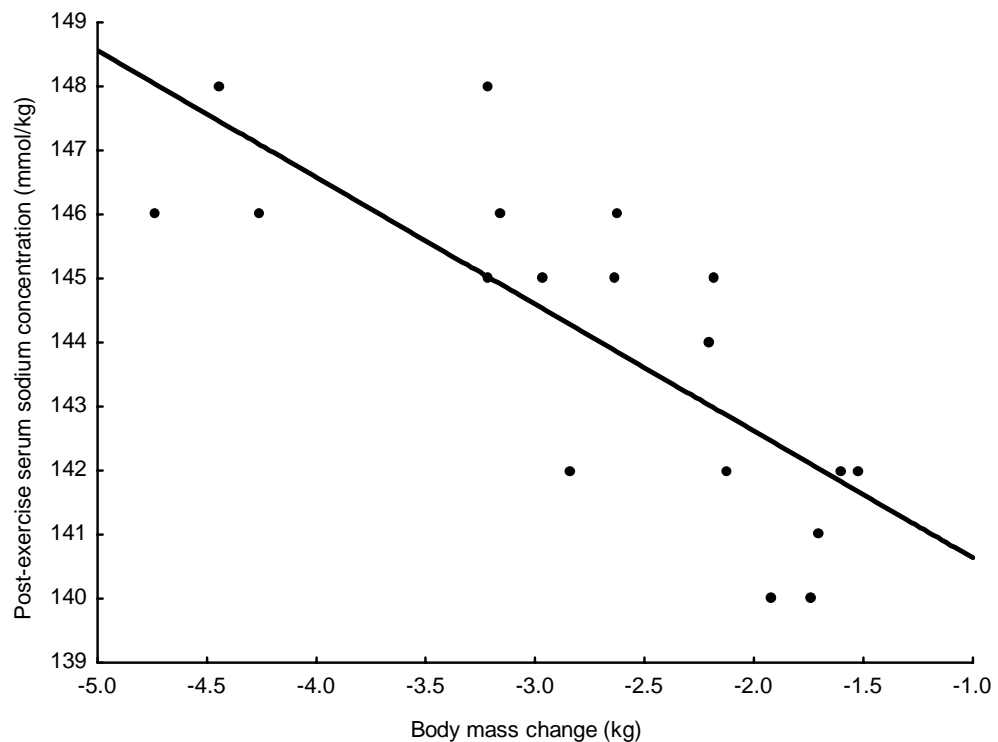
Figure 3: Relationship between post exercise serum [Na⁺] and body mass change during exercise ($p < 0.05$, $r = -0.76$)
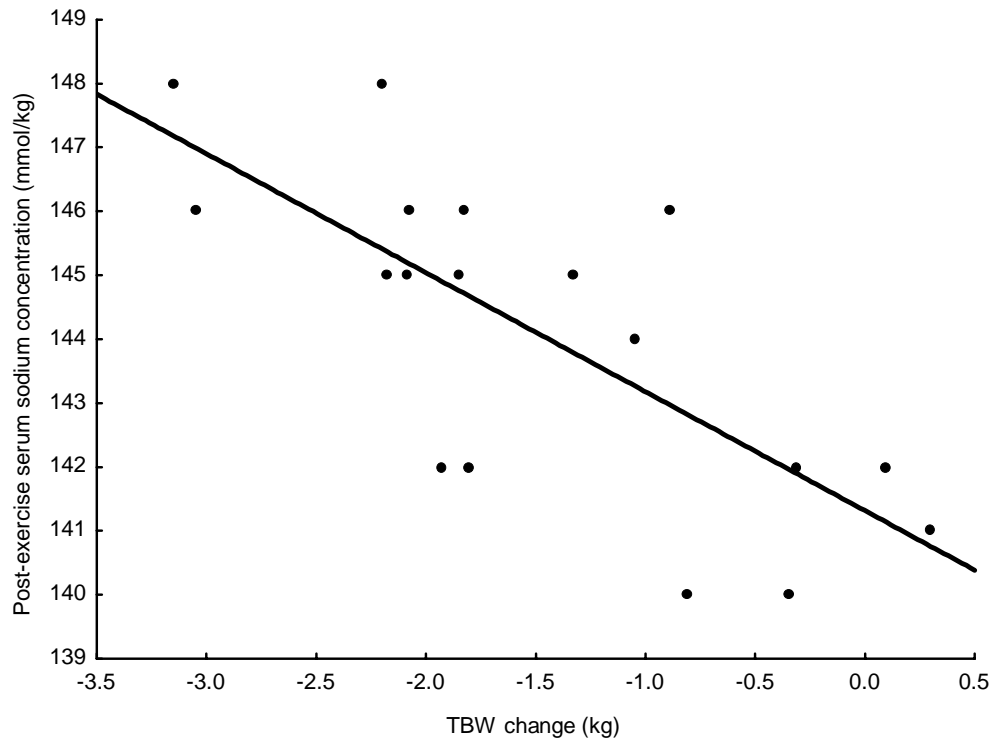
Figure 4: Relationship between post exercise serum [Na$^+$] and change in TBW (kg) during exercise ($p < 0.05$, $r = -0.73$).

Peak core temperature measurements

The mean peak core temperature of the subjects during the exercise was 39.0°C; the highest individual core temperature was 40.3°C. Figure 5 (a, b, c) plots the individual core temperature responses as a function of magnitude during the march. The oscillatory pattern in most subjects indicates the presence of a pacing strategy in which subjects included frequent (up to 4 during the march) rest periods in the shade. The decision to rest seems not to have been determined purely by the intestinal temperature since of approximately 4 separate bouts of rest per subject, the vast majority occurred when the intestinal temperature was less than 39°C (all but two cases). Indeed the highest temperature reached before a rest period was ~40°C.
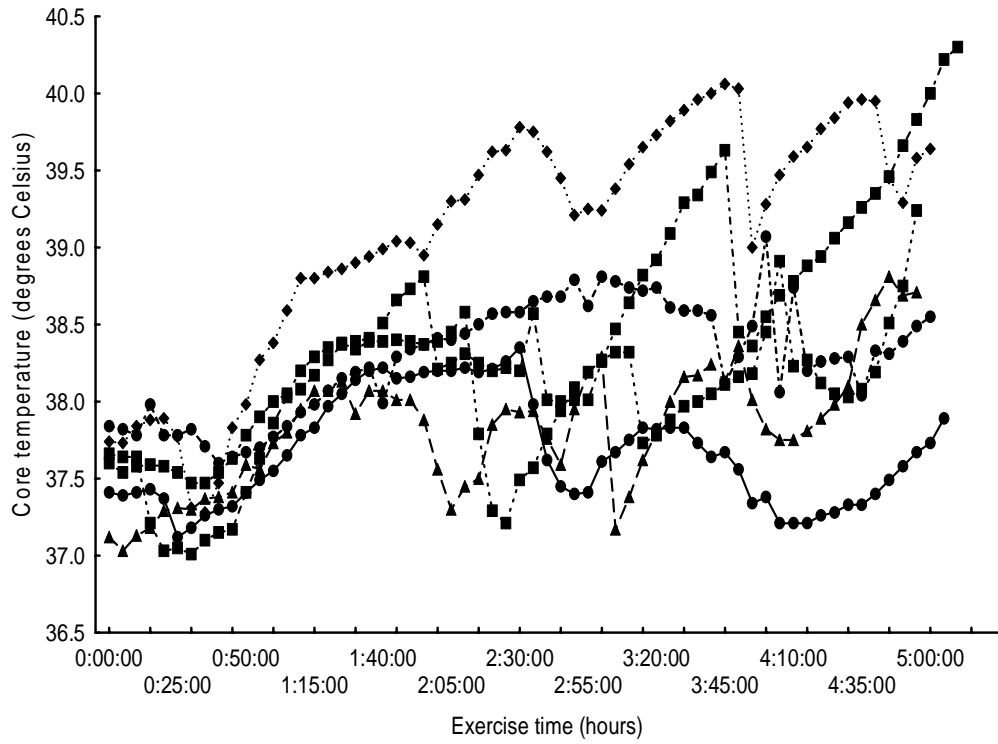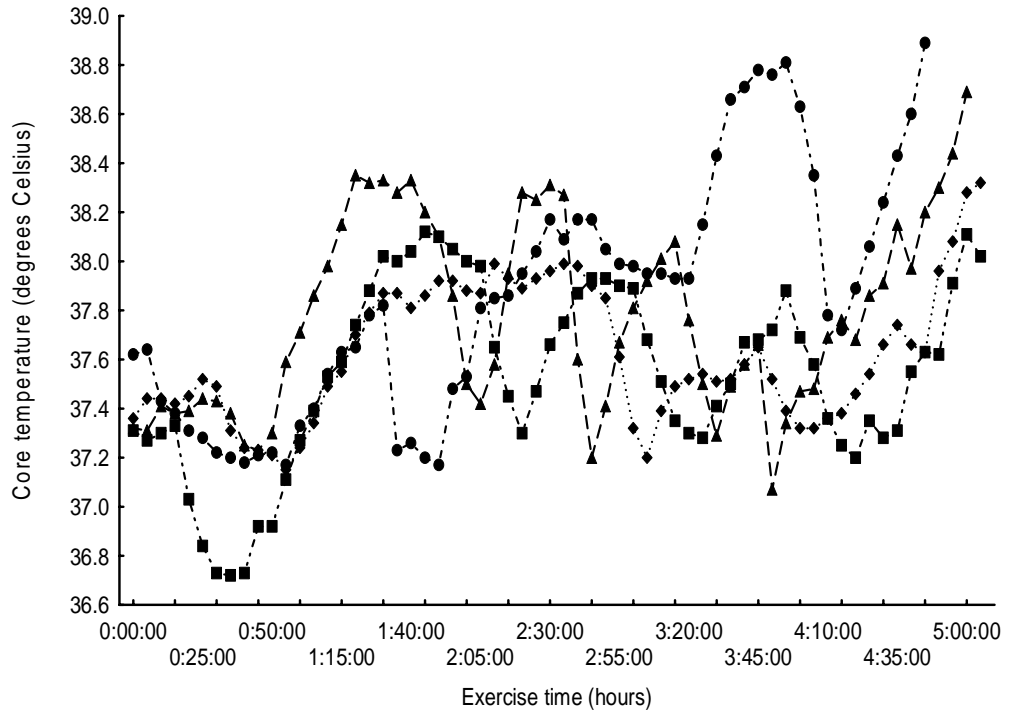
Figure 5a: Core temperature changes during the route march from the

6 subjects with the highest core temperatures
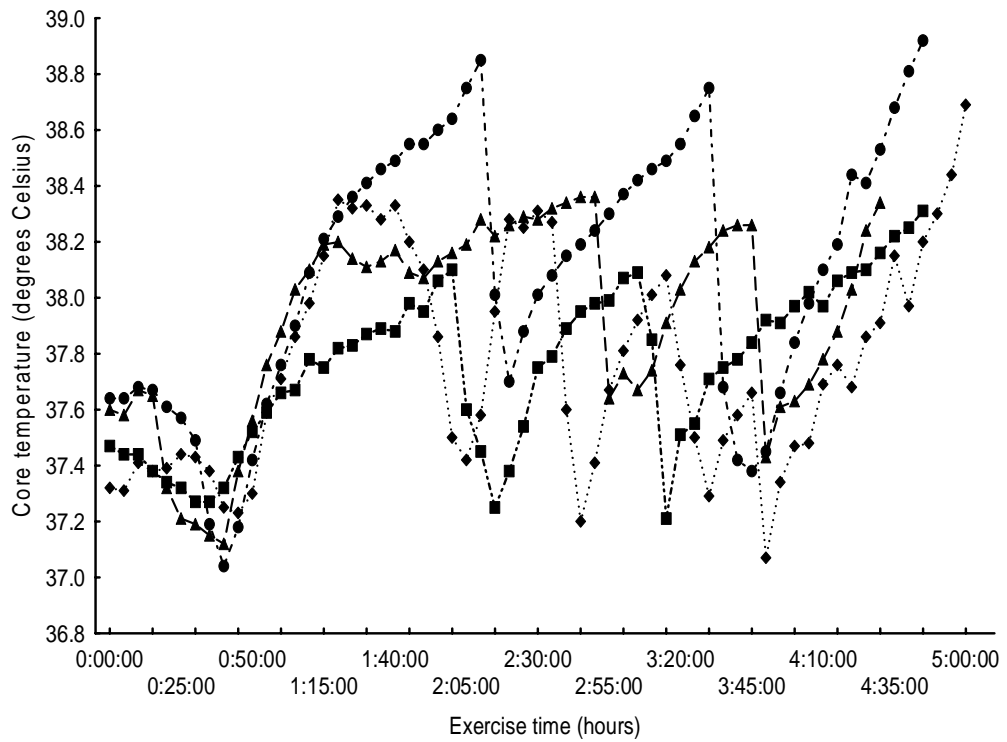
Figure 5b: Core temperature changes during the route march from the

6 subjects with moderate core temperatures

Figure 5c: Core temperature changes during the route march from the 6 subjects with the lowest core temperatures

Total body water measurements

Table 2 presents the pre- and post-exercise TBW results as determined by deuterium oxide dilution and the post-exercise TBW results as determined by oxygen-18 dilution for all the subjects. TBW fell significantly ($p < 0.05$) (1.47 kg) (2.0% body mass) during exercise.

Table 2: TBW changes during a 25km march at 40°C

	Minimum	Mean (±SD)	Maximum
Pre-exercise TBW [kg]	33.36	44.87 (6.0)	54.67
Post-exercise TBW [kg] [deuterium oxide]	31.55	43.39 (6.0)	53.34
Post-exercise TBW [kg] [oxygen-18]	32.86	44.75 (5.3)	54.92
Pre-exercise TBW [% body mass]	52.91	61.50 (3.9)	66.74
Post-exercise TBW [% body mass]	52.42	61.81 (4.3)	68.57
TBW change during exercise [kg]	-3.15	-1.47 (0.99)	0.302
TBW change during exercise [% body mass]	-1.3	0.3 (0.9)	1.8

Figure 6 shows that the change in body mass was significantly related to the change in TBW ($r = 0.77$). However the change in body mass did not accurately predict the changes in TBW as a 1:1 ratio. Rather a 1000g loss in body mass was associated with only a 200g loss in TBW.
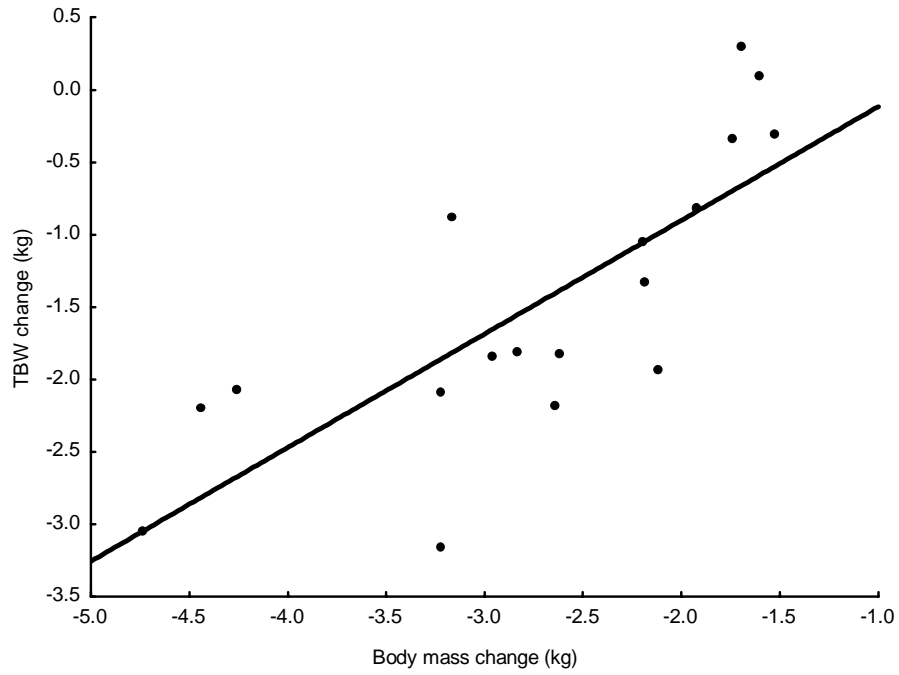
Figure 6: The relationship between changes in body mass and TBW

(p<0.05, r = 0.77)

Weight loss and performance

Figure 7 shows that there was no relationship between the change in body mass and exercise time (p>0.05). Nor was there any relationship (p>0.05) between change in TBW and exercise performance (Figure 8).
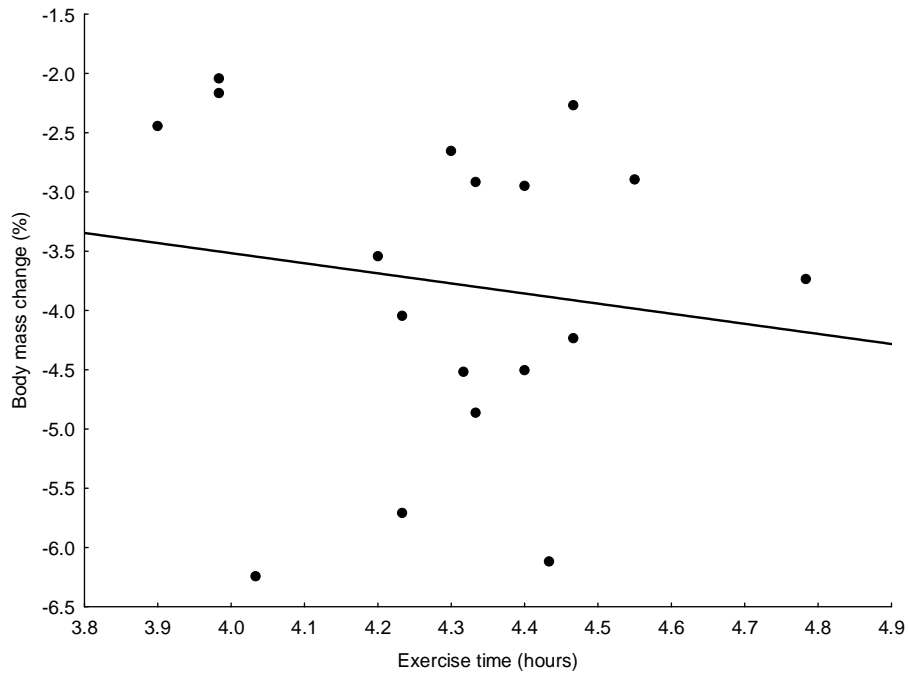
Figure 7: The relationship between exercise time and changes in body

mass and (p>0.05, r = -0.14).
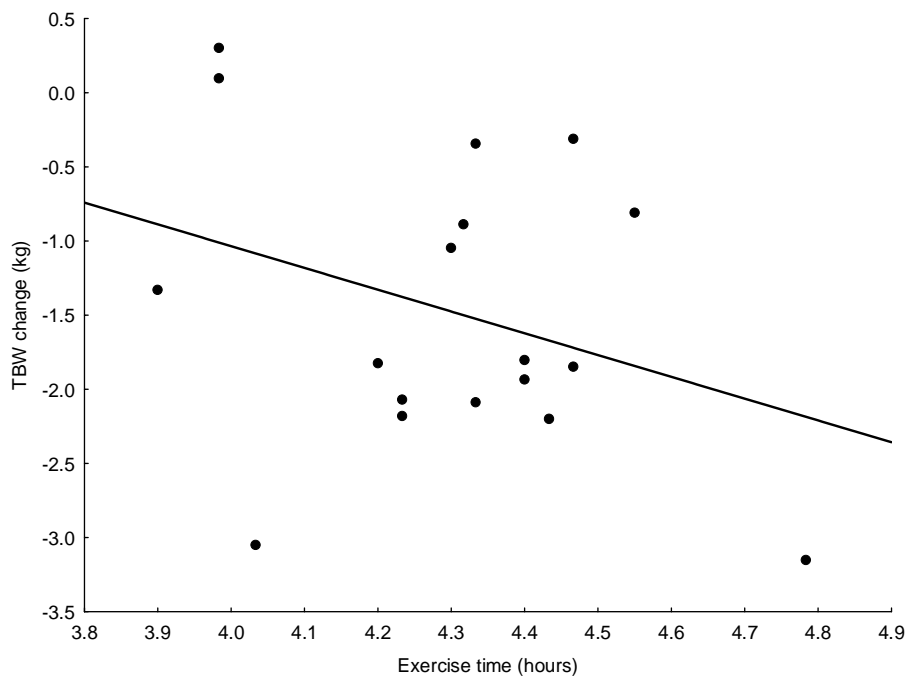
Figure 8: The relationship between exercise time and changes in TBW

and (p>0.05, r = -0.33).

6.4 Discussion

To our knowledge this may be the first reported study of the physiological responses of a relatively large number of fully-burden subjects to competitive exercise in conditions of extreme dry heat while they wore clothing that was somewhat inappropriate for both the activity and the prevailing environmental conditions.

Accordingly, our first important finding was that despite carrying packs of 26 kg and wearing standard issue battle dress, soldiers participating in a competitive 25 km route march maintained safe body temperatures of less than 40.3°C while exercising in environmental conditions that approach those considered to be unsafe for practice and competition by the American College of Sports Medicine.[2] Furthermore, all completed the study successfully and none presented with either the signs or symptoms of "heat illness". Instead the relatively low core body temperatures measured in our subjects indicate that none was under extreme physiological stress or suffering from excessive thermal strain.

Indeed the core body temperatures measured in our subjects were lower than those measured in athletes competing in a 21 km race under significantly less strenuous environmental conditions (mean WBGT of 26.5 °C), some of the subjects in that race reached intestinal temperatures > 40.5°C without developing symptoms.[6,25] Similar high values have been reported in athletes running 8 km in slightly warmer environmental temperatures (mean WBGT of 27 °C).[11] Yet higher values (>41°C) were measured by Robinson [41] in a pair of

runners completing 5km runs in the heat and in a single marathon runner.[31]

The lower temperatures in these subjects would be explained by the relatively lower exercise intensities and hence metabolic rates that can be sustained for exercise lasting ~ 4 hours. In addition an anticipatory pacing strategy [49] exists to ensure that self-paced exercise performance in the heat is impaired before there is a dangerous elevation of body temperature. Figure 5 shows the pattern of individual core temperature changes during exercise. It is clear that the core temperatures fluctuate according to the pacing of each individual. The observed behaviour during the march was that of individuals performing periods of exercise followed by periods of rest, typically stopping, sitting down (in shade when available) and drinking water. The patterns of the core temperatures follow these periods of increased or decreased exertion.

Although the subjects drank profusely during exercise, maintaining rates of fluid intake that exceed by far rates of 400-800 ml/hr achieved by athletes in competition [35], yet their high rates of fluid intake did not explain their low body temperatures. Thus there was no relationship between % body mass loss or the volume of fluid consumed and the peak exercise core temperature (Figures 1 and 2) as now frequently reported.[6,33,46,38]

Accordingly we conclude that the *ad libitum* fluid intake was sufficient to ensure safe thermoregulation during the march in these subjects who were able to self-regulate their pacing strategies to suit the particular environmental conditions. A number of previous studies indicate that *ad libitum* fluid replacement strategies in which between 60-70% of sweat losses are replaced, are sufficient to maintain thermoregulation in athletes despite body mass losses of up to 3%.[24]

The second important finding was that subjects regulated their serum [Na$^+$] and POsm within the normal range while drinking only water *ad libitum* at a mean rate of 1264 ml/hr while sweating an average total of 1789 ml/hr. Although we did not measure the sweat [Na$^+$] in these soldiers, there is no reason to believe they would be lower than values of about 40mmol/L measured in other athletes consuming a typical Western diet. At this sweat [Na$^+$], average total sweat sodium losses during the march would have been >240mmol. Yet despite such large losses that were unreplaced during exercise, serum [Na$^+$] was maintained during exercise. This confirms the now well-established finding that the serum [Na$^+$] can be maintained during exercise without the need for acute sodium replacement during exercise.[17]

Clearly one important contributor to the regulation of the serum [Na$^+$] was the mean body mass loss of 2.73 kg (3.8%) during the exercise. Figures 3 and 4 shows that an increase in TBW and body mass produced a fall in serum [Na$^+$] whereas a fall in TBW and body mass produced a rise in serum [Na$^+$]. This data are compatible with our findings that an increase in body mass (and hence TBW) is the major

determinant of exercise-associated hyponatremia (EAH).[36,43,47,38,18]

Although the magnitude of this body mass loss of nearly 4% is almost double that considered desirable during exercise [44], yet it is clearly the homeostatically-regulated response of these subjects who drank *ad libitum* during exercise. This is because the plasma osmolality and not the body mass is the regulated variable both at rest and during exercise so that drinking according to the dictates of thirst would be expected to produce minimal changes in plasma osmolality and the serum [Na^+].[16] In contrast drinking to stay "ahead of thirst" by "drinking as much as tolerable", [7,4] must cause serum [Na^+] to fall [36,43,47] if renal free water clearance is insufficient to prevent an increase in TBW. This occurs when arginine vasopressin (ADH) secretion is not appropriately suppressed by a decreasing serum osmolality.[43]

Thus we conclude that the *ad libitum* intake of water during a 25 km route march was sufficient to maintain serum [Na^+] despite significant body mass and sweat electrolyte losses. This is compatible with the finding that sodium ingestion is not required to maintain serum [Na^+] during exercise.[17] Rather it is the inappropriate regulation of the TBW that determines the extent to which the serum [Na^+] falls during prolonged exercise.[36]

Our third conclusion is that changes in body mass were not related exactly to changes in TBW according to a 1:1 relationship (Figure 6), so that for each 100g loss of body mass there is a 100ml reduction in

TBW. Furthermore the results of the post-exercise TBW as determined by the deuterium oxide and the oxygen-18 isotopes compared favourably (r=0.98) (Table 2). This is an important finding since it disproves the idea that a second deuterium oxide dose might cause an overestimation of TBW.

This supports our previous findings in soldiers performing prolonged exercise during which their ad libitum water intakes were sufficient to maintain thermoregulation while producing in one group, a 197 g increase in TBW despite a body mass loss of 1.3 kg [38] and in another a 500 g decrease in TBW despite a body mass loss of 1.0 kg.[39]

Similar findings were reported in soldiers performing a 194 km unsupported desert march during which their mean hourly fluid intakes of 458 ml were sufficient to maintain thermoregulation (mean core temperature of 38.1°C) while producing a 300 g increase in TBW despite a body mass loss of 3.3 kg at the end of exercise.[32] Considered in their totality, these findings rekindle the original concept of Ladell [21,22,23] that a body fluid reserve of perhaps up to 2 litres may exist and which may not require replacement in order to insure that whole body fluid homeostasis is maintained during exercise.[37,38] If his fluid volume exists in the gut it would explain why some believe that body mass losses of up to at least 3% may not carry any physiological penalty during prolonged exercise.[22,28,30,46]

Our fourth finding was that performance during the march was unrelated to the extent of the change in either body mass (Figure 7) or TBW (Figure 8). This is an extension of the finding that the amount of fluid ingested during the march also did not predict performance time during the march.

In conclusion, this study extends to much more extreme environmental conditions, than our previous findings [38] that *ad libitum* drinking was sufficient to maintain POsm and serum [Na$^+$], and prevent an excessive rise in core temperature during a 16 km paced march in a WBGT of 24.5°C. In this study we show that in the most extreme conditions yet studied humans were able to maintain POsm, serum [Na$^+$] and safe core body temperatures while drinking water *ad libitum*. They achieved this outcome by (i) adopting a pacing strategy which included resting in the shade when available, (ii) by increasing their rates of *ad libitum* fluid intakes to amongst the highest yet recorded in runners/walkers and (iii) by allowing a small reduction in TBW, the latter presumably to insure the maintenance of serum [Na$^+$] despite a loss of > 200mmol Na$^+$ in sweat.

Our findings that some selected humans are able to perform competitive exercise in these severe environmental conditions are indeed compatible with the historical interpretation that humans are the mammals with the greatest capacity for exercising in extreme heat [15] and that this adaptation must have evolutionary significance.[5,26]

Acknowledgement

6.5 **References**

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