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Dehydration in hot working environments: assessment, prevention and rehydration procedures

by M. H. Stirling

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of

Doctor of Philosophy of Loughborough University

September 2000

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ABSTRACT

This PhD thesis addresses the problem of dehydration during work in hot environments. Many industries in the UK are affected by problems of dehydration. These include the glass-making and metal refinery industries, ship-building, the nuclear industry, firefighting and firefighter training, and other activities where protective clothing is worn. The thesis is written in five parts, with the following aims: 1) To review current literature and available guidelines on the factors affecting dehydration and rehydration, and study the influence of acclimation. The latter was achieved during a laboratory-based experiment with 8 subjects, where diet and activity were strictly controlled, and a sweat electrolyte collection technique was developed. 2) To identify practical and accurate methods of measuring hydration state, which could be used in laboratory work, and ultimately in field-based work. This included a literature review and two laboratory-based experiments, one of which was an extensive repeated measures study using 8 subjects. 3) Several Fire Brigades had expressed concern in the area of dehydration, so a case study was carried out to determine the extent of hydration problems during firefighter training, and provide a solution if a problem was identified. This aim was achieved by taking physiological and subjective measures from 8 fire training instructors and 19 firefighter recruits in their training environment. Following this, a laboratory–based, repeated measures study was carried to assess the physiological and psychological impacts of two controlled drinking regimes versus ad libitum drinking during simulated fire training instructor work. 4) To implement an effective and practical fluid intake regime into firefighter training. This study involved 128 recruits and 88 fire training instructors completing user questionnaires regarding any practical issues that needed to be addressed in order for them to be able to follow the controlled drinking regime. 5) To provide guidance for firefighter recruits and instructors in the form of quick reference information, and where required, more in-depth analyses of body water changes. The results of the thesis are outlined below.

When monitoring the hydration state of people who work in the heat, thirst cannot be relied upon as a method for accurately regulating fluid intake. However, the urinary indices of osmolality, specific gravity and colour (and volume to a lesser extent) provide a combination of accuracy and practicality. During the case study with the Fire Service, it was found that firefighter recruits do not experience significant dehydration problems during hot fire training, whereas fire training instructors do. In an attempt to solve these problems, two controlled fluid intake regimes were employed. They provided attenuation in physiological strain compared to ad libitum drinking during simulated fire instructor work in hot conditions. Subsequently, it was found that an effective fluid intake regime could be successfully implemented into firefighter training, so long as sufficient provision is made in terms of time and availability of fluids. To accompany the fluid intake regime, a guidance document, specifically tailored to the Fire Service, on the effects of dehydration and heat strain, and how to reduce those effects, was produced. In addition, more in-depth analysis of body water changes has been provided. Identifying hydration problems and providing solutions (physiological and practical) took place during work with the Fire Service in this thesis; however the process has generic properties and could be applied elsewhere.
ACKNOWLEDGEMENTS

To: My supervisor, Professor Ken Parsons, for encouragement, support and wisdom throughout my years at Loughborough, I thank you. The Department of Human Sciences, an inspirational and stimulating place to study. Trevor Cole for unlimited technical support and friendship. The many subjects who volunteered to participate in experimental work. Leicestershire Fire and Rescue Service, in particular Andy Dermott and Mick Ayres, for efficient and unquestioning help. The British Federation of Women Graduates for their financial support and encouragement.

And also: My much loved family and close friends for their continuing support and interest. And finally, my husband for his motivation, love, help and tolerance.

This thesis was written in the fond memory of my father.
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### NOTATION

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_D$</td>
<td>DuBois surface area</td>
<td>$m^2$</td>
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<tr>
<td>BW</td>
<td>body weight</td>
<td>$kg$</td>
</tr>
<tr>
<td>BW loss</td>
<td>body weight loss</td>
<td>%</td>
</tr>
<tr>
<td>Ca</td>
<td>clothing weight after an event</td>
<td>$kg$</td>
</tr>
<tr>
<td>Cb</td>
<td>clothing weight before an event</td>
<td>$kg$</td>
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<td>Cl</td>
<td>chloride ion</td>
<td>-</td>
</tr>
<tr>
<td>ECF</td>
<td>extracellular fluid</td>
<td>-</td>
</tr>
<tr>
<td>ECF&lt;sub&gt;om&lt;/sub&gt;</td>
<td>extracellular fluid osmolality</td>
<td>mosmol / kg H&lt;sub&gt;2&lt;/sub&gt;O</td>
</tr>
<tr>
<td>$H^+$</td>
<td>free hydrogen ion</td>
<td>-</td>
</tr>
<tr>
<td>Hb</td>
<td>haemoglobin</td>
<td>g/ml</td>
</tr>
<tr>
<td>HCO&lt;sub&gt;3&lt;/sub&gt;⁻</td>
<td>bicarbonate ion</td>
<td>-</td>
</tr>
<tr>
<td>HCl</td>
<td>hydrochloric acid</td>
<td>M</td>
</tr>
<tr>
<td>Hct</td>
<td>haematocrit</td>
<td>%</td>
</tr>
<tr>
<td>HR</td>
<td>heart rate</td>
<td>bpm</td>
</tr>
<tr>
<td>ICF</td>
<td>intracellular fluid</td>
<td>-</td>
</tr>
<tr>
<td>ICF&lt;sub&gt;om&lt;/sub&gt;</td>
<td>intracellular fluid osmolality</td>
<td>mosmol / kg H&lt;sub&gt;2&lt;/sub&gt;O</td>
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<tr>
<td>K⁺</td>
<td>potassium ion</td>
<td>-</td>
</tr>
<tr>
<td>M</td>
<td>metabolic free energy production</td>
<td>W m⁻²</td>
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<tr>
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<td>mmol/l</td>
</tr>
<tr>
<td>PO₄&lt;sup&gt;3-&lt;/sup&gt;</td>
<td>phosphate ion</td>
<td>-</td>
</tr>
<tr>
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<td>mmol/l</td>
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<tr>
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<td>mosmol / kg H&lt;sub&gt;2&lt;/sub&gt;O</td>
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<tr>
<td>PV</td>
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<td>l</td>
</tr>
<tr>
<td>rh</td>
<td>relative humidity</td>
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</tr>
<tr>
<td>Sa</td>
<td>subject weight after an event</td>
<td>kg</td>
</tr>
<tr>
<td>Sb</td>
<td>subject weight before an event</td>
<td>kg</td>
</tr>
<tr>
<td>Sw&lt;sub&gt;evap&lt;/sub&gt;</td>
<td>sweat evaporated</td>
<td>kg</td>
</tr>
<tr>
<td>Sw&lt;sub&gt;K&lt;/sub&gt;</td>
<td>sweat potassium</td>
<td>µg</td>
</tr>
<tr>
<td>Sw&lt;sub&gt;T&lt;/sub&gt;</td>
<td>total sweat loss from the body</td>
<td>kg</td>
</tr>
<tr>
<td>Sw&lt;sub&gt;Na&lt;/sub&gt;</td>
<td>sweat sodium</td>
<td>mg</td>
</tr>
<tr>
<td>SwR</td>
<td>sweat rate</td>
<td>l/hr⁻¹</td>
</tr>
<tr>
<td>Sw&lt;sub&gt;tr&lt;/sub&gt;</td>
<td>sweat trapped in clothing</td>
<td>kg</td>
</tr>
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<td>air temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{ma}$</td>
<td>mean aural temperature</td>
<td>°C</td>
</tr>
<tr>
<td>TBW</td>
<td>total body water</td>
<td>l</td>
</tr>
<tr>
<td>TBW&lt;sub&gt;om&lt;/sub&gt;</td>
<td>total body water osmolality</td>
<td>mosmol / kg H&lt;sub&gt;2&lt;/sub&gt;O</td>
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<td>Definition</td>
<td>Unit</td>
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<td>-----------</td>
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<td>$T_{core}$</td>
<td>core temperature</td>
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<tr>
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<td>dry bulb temperature</td>
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</tr>
<tr>
<td>$T_g$</td>
<td>globe temperature</td>
<td>°C, K</td>
</tr>
<tr>
<td>$T_{nw}b$</td>
<td>natural wet bulb temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{or}$</td>
<td>oral temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_r$</td>
<td>mean radiant temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{re}$</td>
<td>rectal temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{sk}$</td>
<td>mean skin temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{wet}$</td>
<td>water temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{wb}$</td>
<td>aspirated wet bulb temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$U_{col}$</td>
<td>urine colour</td>
<td>-</td>
</tr>
<tr>
<td>$U_K$</td>
<td>urine potassium</td>
<td>mEq.l$^{-1}$</td>
</tr>
<tr>
<td>$U_{Na}$</td>
<td>urine sodium</td>
<td>mEq.l$^{-1}$</td>
</tr>
<tr>
<td>$U_{osm}$</td>
<td>urine osmolality</td>
<td>mosmol / kg H$_2$O</td>
</tr>
<tr>
<td>$U_{pH}$</td>
<td>urine pH</td>
<td>-</td>
</tr>
<tr>
<td>$U_{sg}$</td>
<td>urine specific gravity</td>
<td>-</td>
</tr>
<tr>
<td>$U_{temp}$</td>
<td>urine temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$U_{vol}$</td>
<td>urine volume</td>
<td>ml</td>
</tr>
<tr>
<td>$V_{O_2}$</td>
<td>oxygen uptake</td>
<td>ml.kg.min$^{-1}$.l.min$^{-1}$</td>
</tr>
<tr>
<td>$V_{O_2max}$</td>
<td>maximal oxygen uptake</td>
<td>ml.kg.min$^{-1}$</td>
</tr>
<tr>
<td>WBGTT</td>
<td>wet bulb globe temperature</td>
<td>°C</td>
</tr>
</tbody>
</table>

**Greek**

*Symbol | Definition

$\Delta$ | change
Aims of the Thesis

The overall aim of the thesis was to draw together and evaluate, using laboratory and field experiments, current information and guidance on dehydration and rehydration, so that it may be developed where necessary, and applied in practical situations where physical work is carried out in hot environments.

The specific aims of the thesis were as follows: 1) To review current literature and available guidelines on the factors affecting dehydration and rehydration. 2) To develop practical and accurate methods of measuring hydration state, which could be used in laboratory work, and ultimately in field-based work. 3) To determine the extent of hydration problems during firefighter training (for instructors and recruits), as several Fire Brigades had expressed concern in this area. 4) To implement an effective and practical fluid intake regime into firefighter training. 5) To provide guidance for firefighter recruits and instructors in the form of quick reference information, and where required, more in-depth analyses of body water changes.

Thesis Outline

The thesis is set out in five sections, each containing several chapters. The content of each of the sections is detailed below.

Part I: Overview of dehydration

This section aimed to review the information currently available on dehydration, rehydration and also acclimatisation to work in the heat, as a basis for the applied work that would be carried out later in the thesis.
Part II: Methods of assessing hydration state

In order to be able to measure dehydration, it was necessary to first assess measures of hydration state. This section identified methods that were accurate (reliable, sensitive and valid) and practical, both in a laboratory setting and during field work.

Part III: A case study: The Fire Service

Firefighters often carry out work in hot environments. The Fire Service is currently provided with very little information on how to remain well-hydrated during work in the heat, and as a result incur problems of dehydration. In this section, the extent of dehydration was measured in different groups of Fire Service personnel, and the effectiveness of a fluid replacement regime was established.

Part IV: Application of theory: Providing practical methods of hydration control in industry

In this section, both in depth and quick reference information on body fluid regulation is provided. The practical considerations of implementing a fluid regime were addressed, and a guidance document (specifically tailored to the Fire Service) was produced.

Part V: Discussion and conclusions

The overall discussion and conclusions of the thesis.
Part I

Overview of dehydration
PART I : OVERVIEW OF DEHYDRATION

Part I aims to: 1) provide existing information in the area of dehydration in order that there is a sound basis of understanding throughout the rest of the thesis, and 2) establish the extent of acclimation that may take place under certain conditions, and what bearing this may have on dehydration in a work situation.

Chapter 1 describes the possible causes of dehydration and how the physiological and cognitive effects are manifested. Much research has been carried out over the years which has provided information and advice on reducing the effects of dehydration, and this is also summarised in Chapter 1.

Chapter 2 considers heat acclimation and the extent of physiological and biochemical changes that take place when a subject consumes a moderate amount of salt in their diet. The study also provided an opportunity to develop a sweat sampling technique, which was used in subsequent studies.
Chapter 1
Chapter 1

LITERATURE REVIEW OF DEHYDRATION

1.1 Introduction
Many occupations require people to perform work in thermally stressful environments. Under such conditions, relatively high sweating rates can be achieved in an attempt to regulate body temperature (Noakes et al, 1985; Sawka & Wegner, 1988). It has long been recognised that reductions in body water volume will elevate core temperature and heart rate during physical work in the heat, and can impair performance (Adolph, 1947; Eichna et al, 1945; Ladell, 1955; and Pitts et al, 1944). This chapter aims to provide an introduction to the process of dehydration: how it occurs, why it occurs, the effects it has on human health and performance (both physical and mental) and how to reduce its effects. Each of these issues is discussed in greater depth in subsequent chapters.

1.2 The components of dehydration

1.2.1 Thermoregulation
Where human thermal environments provide a tendency for positive body heat storage, the body’s thermoregulatory system responds to attempt to increase heat loss (Parsons, 1993c). During physical exercise metabolic rate is increased, often up to 15 times that of the resting level (Sawka, 1988), to provide energy for contracting skeletal muscles. Most of this metabolism is released as heat, which needs to be dissipated in order to achieve body heat balance. In response to heat stress, warm blood is diverted from the body’s ‘core’ to its ‘shell’, the vascular cutaneous bed dilates, hence increasing skin blood flow, and the sympathetic nervous system activates the sweating mechanism where necessary. When the environmental temperature exceeds the skin temperature, the body is gaining heat by convection, radiation and conduction, so evaporation of sweat is the only avenue for heat loss (apart from a small amount of heat loss through respiration). Therefore, in hot environments, a considerable amount of body water is lost via sweat gland secretion.
to enable evaporative cooling of the body (Wenger, 1972). Work in the heat imposes a competitive demand on the body, requiring it to serve both the active muscles with oxygen (to sustain performance), whilst at the same time transporting heat from the deep body tissues to the periphery (thermoregulation). Consequently, a period arises when the body can no longer serve both systems adequately, and as a result the increased sweat loss impinges upon the available blood volume, making it increasingly more difficult for the cardiovascular system to support the combined stress of exercise and heat. The amount of body fluid lost as sweat can vary greatly and sweating rates of 11.h\(^{-1}\) are not uncommon (Sawka, 1992). If water is not replaced, dehydration will occur.

1.2.2 Dehydration

Water is the largest component of the human body, representing about 60% (range 45-70%) of total body weight (Sawka, 1992). Under normal, familiar conditions, an individual’s water balance remains relatively stable over time (Thomson et al, 1996). However, a reduction in the amount of body water can have serious or even fatal consequences, because virtually all physiological systems will be affected (physiology and regulation of the body fluids is discussed in detail in Chapter 10). Water is used within the body as a medium for biochemical reactions and for transportation of body solutes. It is the main component of plasma, which is essential in the maintenance of blood volume. Plasma is also the initial source of fluid for sweat production. Sweat rates exceeding 2 litres/hour can be maintained for several hours by trained and acclimated people exercising in warm and humid conditions (Shirreffs & Maughan, 2000). Unless this water is replaced through drinking, the volume of blood in the body will be reduced due to the loss of plasma, making it more difficult for the cardiovascular system to support the combined stress of physical work and heat. In cases of heat-exercise, the cardiovascular system is supported by the pressure gradients acting across the body cells. By processes of osmotic, tissue and hydrostatic pressures, blood volume is maintained using water from other areas of the body. However, continuous heat–exercise will continue to deplete the body’s water supplies leading to greater pressure on the heart. Thirst alone should not be relied on as an indicator of the need to drink, since the body will have lost 1-2% of its water and experienced performance decrements before a person feels thirsty (Greenleaf, 1992). (Thirst is discussed in depth in Chapter 3). If blood volume is reduced, then more
pressure is put on the heart to keep an adequate blood supply to all the areas of the body needing blood, and there will be an increase in heart rate. This process of dehydration reduces the volume of the body fluids and makes them more concentrated. During hypohydration, sweat rate (Fortney et al, 1981b; Nadel, 1979) and skin blood flow (Claremont et al, 1976; Fortney et al, 1981a; Nadel et al, 1980) are reduced, thus limiting evaporative heat loss. For this reason, the body is less able to dissipate heat and core temperature rises. There is also an increase in heart rate, which is associated with decreased ventricular filling pressure and cardiac stroke volume (Nadel et al, 1980; Wyndham, 1973). In addition to water loss, sweating also results in the loss of electrolytes, and possibly an imbalance. (Electrolyte loss during thermal sweating is discussed in detail in Chapter 2).

Throughout this chapter and thesis, the following body fluid states will be referred to (Greenleaf, 1992):

*Euhydration* refers to ‘normal’ body water content.

*Hypohydration* refers to body water deficit.

*Dehydration*, which is the more common term, denotes the dynamic loss of body water, or the transition from euhydration to hypohydration.

### 1.3 The causes of dehydration

The three main factors that influence normal dehydration are the environment, the work done and the clothing worn (dehydration can also be caused by illness or drug use, but they are considered beyond the scope of this thesis). The relative importance of each is situation dependent, but generally, situations that favour sweat loss encourage dehydration.

#### 1.3.1 Environment

Environmental heat stress is determined by the ambient temperature, relative humidity, wind velocity and radiation (both direct and reflected). In compensable environmental heat stress conditions, the thermoregulatory system can offset increased body heat storage to maintain steady-state core temperature (Latzka et al, 1998). In high ambient temperatures, sweating is the major route by which heat is removed from the body, and hence, in the absence of fluid replacement, dehydration
occurs. Daily water losses of 15 litres are commonly reported for workers in the
desert (Adolph & Dill, 1938).

Parsons (1995) discusses the merits of the wet bulb globe temperature (WBGT) index
(ISO 7243, 1989), which allows a fast diagnosis of the heat stress to which an
individual is exposed. It is calculated as follows:

\[ \text{WBGT} = 0.7 T_{\text{wb}} + 0.2 T_g + 0.1 T_a \]

for outside conditions with a radiant load, or

\[ \text{WBGT} = 0.7 T_{\text{wb}} + 0.3 T_g \]

for indoor conditions or with no solar load

(Eq. 1.1)

Where \( T_{\text{wb}} \) is the temperature (in °C) of a natural wet bulb thermometer, \( T_g \) is the
temperature of a 150mm diameter black globe thermometer, and \( T_a \) is air temperature
(\( T_a = T_{db} \), which is the temperature of a dry bulb thermometer). Some typical
environmental scenarios (measured using WBGT) and responses to exercise are
shown in Table 1.1 (Gleeson, 1998). The highest sweat rate and heart rate are
observed for exercise in hot, humid conditions. There will be less evaporative heat
loss in these conditions, and thus a greater rise in core temperature, inducing a greater
sweat rate. Rapid dehydration will take place in such conditions without fluid
replacement.

<table>
<thead>
<tr>
<th>Relative humidity (%)</th>
<th>( T_{db} )</th>
<th>( T_a )</th>
<th>( T_g )</th>
<th>WBGT</th>
<th>Sweat rate (litres/hour)</th>
<th>Heart rate (beats/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>22.0</td>
<td>15.3</td>
<td>30.0</td>
<td>18.9</td>
<td>0.4</td>
<td>150</td>
</tr>
<tr>
<td>50</td>
<td>35.0</td>
<td>26.7</td>
<td>45.0</td>
<td>31.2</td>
<td>1.0</td>
<td>155</td>
</tr>
<tr>
<td>90</td>
<td>35.0</td>
<td>33.4</td>
<td>42.0</td>
<td>35.3</td>
<td>1.6</td>
<td>165</td>
</tr>
</tbody>
</table>

Table 1.1: Typical sweat rates and heart rates after 30 mins exercise at about 60% \( \text{VO}_2 \text{ max} \) under
different environmental conditions (Gleeson, 1998)
1.3.1 Work rate

When all other factors are held constant, work load directly determines heat production and hence the increase in core temperature (therefore, high intensity exercise can cause a substantial rise in body temperature even in a cool environment). Approximately 80% of the energy released during exercise is heat (Brotherhood, 1984). Compared to steady dynamic work, time weighted averaging can be applied to intermittent mixed static and dynamic work without any disproportionate physiological effects (for the periods of work and rest studied), but care must be taken to ensure that any activity sampling procedure results in a truly representative sample (Graveling & Morris, 1995). During exercise at an intensity equivalent to about 89-90% VO₂ max, the body heat production in a fit individual may exceed 1000 W (Gleeson, 1998). This could potentially cause body temperature to rise by 1°C every 5-8 minutes (Hayms, 1984) if there were no change in the body’s heat dissipation mechanisms, and lead to serious heat illness. Higher sweat rates are produced at higher work rates to attenuate this rise in body temperature, encouraging dehydration.

1.3.2 Clothing

The need to wear protective clothing may lead to intolerable heat strain, particularly in hot environments, due to the body’s diminished capacity for heat dissipation. Protective clothing therefore causes a downward shift in the temperature level at which heat strain occurs (Havenith, 1999). When the body’s evaporative cooling requirement exceeds the climate’s cooling capacity (Belding & Kamon, 1973; Lind, 1963, 1973), an individual may be at risk of uncompensable heat stress (UCHS). This can occur when workers, such as hazardous material clean-up teams, firefighters, foundry workers and soldiers on chemical battlefields, wear protective clothing (Kraning & Gonzalez, 1991).

Protective clothing increases insulation and decreases the body’s ability to dissipate heat. The extent to which it does this can be considered under five categories: insulation, ventilation, perspiration, circulation and weight (Graveling, 1998), which, in combination with the body’s responses, can be said to form the clothing microenvironment; that is, the air layer between the skin and the material (and when several layers of material are present, that between and on the outside of the material.
layers) (Figure 1.1). Levels of both insulation and ventilation can provide protection but at the same time be problematic. For example, high insulation and low ventilation will protect a firefighter from the harsh external environment, but will severely impair the heat transfer from the body. Heat loss via the evaporation of sweat will be largely determined by the water vapour pressure (humidity) of the air close to the body surface (Gleeson, 1998). The local humidity may be high if highly insulated, poorly ventilated or impermeable clothing is worn. In this case, sweat may begin to drip off the skin, rather than evaporate, reducing heat loss via this route. Heat strain whilst wearing impermeable clothing in a relatively cool environment may be less than expected, due to sweat vapour condensing on the inside of the fabric, establishing an internal circulation, which transfers heat from the body to the clothing and then to the environment (Hanson, 1998). In addition, heavy or bulky garments may add to the thermal load, either passively (weight) or by creating a restraining influence on movement.

Knowledge of the magnitude of physiological strain that humans can tolerate, and the factors which modify this tolerance, is essential when seeking to establish operational guidelines for safe performance in the heat (Pandolf et al, 1985). Methods of assessing potential heat stress in the workplace have existed for some time in the form of British and International Standards concerning the ergonomics of the thermal environment (ISO 7243, 1989; BS EN 12515, 1997). However, because most forms of personal protective equipment (PPE) either have a higher insulative value than that assumed or are water vapour impermeable, these standards cannot be accurately
applied to workers wearing PPE (Hanson, 1998). Therefore, a new British Standard is being developed to allow interpretation of the existing standards for workers wearing PPE.

The high sweat rates required to attenuate the rise in core temperature when wearing protective clothing cause dehydration. However, lengthy procedures are often required in order to drink whilst wearing protective clothing, and this may deter individuals from attempting to drink, or at least limit the amount that can be consumed in the time available.

1.3.4 Thirst
Since thirst is not initiated until water loss constitutes approximately 1% of body weight (Adolph, 1947; Greenleaf, 1992), it is not an efficient index of body water requirements (Engell, 1987). Ad libitum drinking results in incomplete fluid replacement. Adolph (1947) noted that body weight losses of 2-3% were commonplace when working in the desert, even when water was plentiful and palatable. In a study by Szlyk et al (1989a), 40% of the young adult male subjects were classified as reluctant drinkers during a simulated 6 hour desert walk, as they maintained body weight loss in excess of 2%, despite the continual availability of cool water. The sensation of thirst is discussed in more detail in Chapter 3.
1.4 The consequences of dehydration

1.4.1 Physiological effects

There are many adverse effects of dehydration on humans including the beginning of impaired exercise thermoregulation at about 1% of body water loss, leading to likely collapse at about 7% loss, when exercise and heat are combined (Table 1.2).

<table>
<thead>
<tr>
<th>% body water loss</th>
<th>Litres for an 80 kg man</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8</td>
<td>Thirst threshold at rest, decreased thermoregulation during exercise, leading to reduced physical work capacity</td>
</tr>
<tr>
<td>2</td>
<td>1.6</td>
<td>Stronger thirst, vague discomfort, loss of appetite, sense of oppression</td>
</tr>
<tr>
<td>3</td>
<td>2.4</td>
<td>Increasing haemoconcentration, dry mouth, reduction in urine output</td>
</tr>
<tr>
<td>4</td>
<td>3.2</td>
<td>Increased effort in exercise, flushed skin, impatience, apathy, physical work capacity reduced by 20-30% (reduced by up to 50% in the heat)</td>
</tr>
<tr>
<td>5</td>
<td>4.0</td>
<td>Difficulty in concentrating, headache, impatience, sleepiness</td>
</tr>
<tr>
<td>6</td>
<td>4.8</td>
<td>Severe impairment in exercise temperature regulation, increased HR, risk of heat stroke, increased rate of breathing leading to tingling and numbness of the extremities</td>
</tr>
<tr>
<td>7</td>
<td>5.6</td>
<td>Likely collapse if combined with heat and exercise</td>
</tr>
<tr>
<td>8</td>
<td>6.4</td>
<td>Dizziness, laboured breathing in exercise, mental confusion</td>
</tr>
<tr>
<td>10</td>
<td>8.0</td>
<td>Spastic muscles, inability to balance with eyes closed, general incapacity, delirium, swollen tongue</td>
</tr>
<tr>
<td>11</td>
<td>8.8</td>
<td>Circulatory insufficiency, marked haemoconcentration, marked decreased blood volume, failing renal function</td>
</tr>
<tr>
<td>15-20</td>
<td>11.2 – 16.0</td>
<td>Death</td>
</tr>
</tbody>
</table>

People who begin physical work with a previously incurred fluid deficit display an impaired ability to dissipate heat during subsequent exercise. They experience a faster rise in core temperature and heart rate; this effect is exaggerated when activity is performed in a hot environment (ACSM, 1996). Several investigators (Montain & Coyle, 1992; Rothstein & Towbin, 1947) have found that the magnitude of increase in core temperature and heart rate are graded in the amount of dehydration accrued during exercise. Core temperature will rise by 0.1-0.4°C for each percent decrease in body weight (depending on exercise intensity and environmental conditions) (Sawka, 1988). Table 1.3 is a comparison of studies that investigated the elevation of core
temperature and the severity of hypohydration. Conclusions based on inter-investigation comparisons, however, can be tenuous because of differences in subject populations, environmental conditions, exercise intensities and test methodologies (Sawka et al, 1984).

Table 1.3: Thermoregulatory responses to varying hydration levels

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Test conditions</th>
<th>Rise in $T_{core}$ for each % decrease in BW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adolf et al</td>
<td>1947</td>
<td>Progressive dehydration in a variety of field &amp; lab conditions</td>
<td>~0.2°C</td>
</tr>
<tr>
<td>Gisolfi &amp; Copping</td>
<td>1974</td>
<td>Prolonged heat exposure ($T_e=34^\circ$C, rh=33%) with heavy exercise (74% VO$_{2\max}$)</td>
<td>0.4°C (after BW loss of 2%)</td>
</tr>
<tr>
<td>Greenleaf &amp; Castle</td>
<td>1971</td>
<td>49% VO$_{2\max}$ in moderate environment ($T_e=24^\circ$C, rh=50%) based on interpolation from 5% BW loss</td>
<td>0.1°C</td>
</tr>
<tr>
<td>Sawka et al</td>
<td>1985</td>
<td>Prior hypohydration levels of 3, 5 and 7%, followed by 140 mins of exercise-heat exposure (49°C, 20% rh)</td>
<td>0.12-0.18°C</td>
</tr>
<tr>
<td>Strydom &amp; Holdsworth</td>
<td>1968</td>
<td>2 hypohydration levels: 3-5% and 5-8% during mining work (only 2 subjects)</td>
<td>Higher core temperature during the 5-8% level</td>
</tr>
</tbody>
</table>

In moderate environmental conditions, the loss of a relatively large amount of body water (6-7%) has a minimal effect on maximal aerobic power (Buskirk et al, 1958; Saltin, 1964), but may reduce physical work capacity by 20% (Saltin, 1964), ie. following dehydration, a person could still work at the same rate to supply oxygen to the muscles, but work time would be markedly reduced. Well-trained individuals will show smaller decreases in work time than less trained individuals in this situation. In combination with a hot environment, dehydration is most apparent in tasks requiring stamina; with a body weight loss of 4%, there may be a decrease of almost 50% in physical work capacity and a loss of almost 30% of aerobic power (Craig & Cummings, 1966), and therefore maximal performance (Figure 1.2). Dehydration has a minimal effect on performance in short, explosive, highly anaerobic events such as weightlifting (Wilmore et al, 1994). Reaction time is increased with dehydration, as is the effort required to perform simple tasks (Wilmore et al, 1994).
1.4.2 Cognitive effects

The effects of dehydration on mental performance are poorly understood. The effects of climate on mental performance have been more widely reported, but such studies have tended not to report information about the rise in body temperature or sweat loss from which the amount of dehydration could be estimated. However, the decline in the efficiency of mental functions and physical work output as a result of increased thermal stress is well established (Pepler, 1964), and that this is specifically related to the degree of elevation of core temperature. The heat stress threshold at which cognitive performance is adversely affected depends upon a complex interplay of factors, such as the degree of thermal stress, duration of exposure, acclimatisation, level of tolerance of individuals, degree of arousal, clothing worn, relative work intensity, skill, training status, motivation and a number of combinations of stressors (Ramsey, 1995).

Generally, it seems that simple reaction time, speed and accuracy of response in complex reaction tasks, vigilance (Grether, 1973), tracking tasks (Ramsey, 1975), and mental reasoning (above 38°C) (Lampietro, 1965) are all reduced above temperatures of about 30°C. These effects are not influenced by gender (Bell, 1978).

1.4.3 Heat related illness

Heat illness is associated with an excessive storage of body heat. The term heat illness encompasses a spectrum of disorders, ranging in intensity and relative severity: from mild cardiovascular and central nervous system disturbances exhibited when suffering from hypotension or fainting (syncope), to more serious cases of heat-stroke,
which may result in irreparable damage to the brain, kidneys, liver and circulatory systems (Costrini et al, 1979).

Several types of heat illness have been defined by Bauman (1995). The less serious conditions of syncope and heat oedema (associated with hypohydration and electrolyte imbalance) are classified among the early stages of heat illness, which lead eventually to heat exhaustion and heat stroke (Thomson et al, 1996). Heat exhaustion is further divided into two main categories, resulting from a specific level of water depletion and salt depletion respectively (Bauman, 1995).

Salt depletion dehydration (negative salt balance) (discussed in detail in Chapter 2) results after several days of prolonged exposure to a given heat stress and is more common in the unacclimatised individual who has not adequately developed a salt conserving mechanism (Sohar et al, 1962). It results in a reduction of plasma volume, cardiac output and blood pressure. It is neither characterised by thirst, nor relieved by administration of salt-free fluids (Pandolf et al, 1988). Water depletion dehydration can cause acute illness within hours of exposure. Casualties experience a great thirst, which can be alleviated by administration of water (Elkinton et al, 1946).

The aetiology of heat cramps has been discussed by a number of reviewers (Dinman & Horvath, 1984). Although the exact mechanism is unknown, heat cramps tend to occur in individuals who have lost a large volume of sweat, who have been drinking unsalted water, and have excreted little urine (Leithead & Lind, 1964).

In summary, maintaining physical and mental effectiveness requires individuals to be very close to euhydration. If not, they suffer from significantly impaired performance, which affects their ability to carry out their task in the workplace. In addition, they will become more susceptible to the effects of heat illness.

1.5 Reducing the effects of dehydration

1.5.1 Acclimatisation

Physical performance in a hot environment is primarily affected by a subject’s state of aerobic fitness (Shapiro et al, 1981), heat acclimatisation status, and hydration level
Repeated exposure to prolonged periods of physical work in the heat leads to a gradual improvement in the ability to eliminate excess body heat, thereby reducing the risk of heat illness. Such a process is called 'heat acclimatisation' if achieved by exposure to an environmental stress (eg. Graveling et al, 1988), or 'heat acclimation' when the effect is produced as a result of artificial exposure to heat (eg. Stirling & Parsons, 1998). At the onset of exercise, sweating commences earlier in the acclimatised as compared to the unacclimatised individual, improving ability to tolerate heat. As a result, skin temperatures are lower and a more favourable gradient is established (Wilmore & Costill, 1994). The sweat produced when a person is acclimatised tends to be more dilute than when in an unacclimatised state, and so this facilitates the efficient conservation of electrolyte stores. As a consequence of becoming acclimatised or acclimated, a person is able to work in a hot environment under far less physiological strain, and continue working for a considerably longer time than when not acclimatised (Bass, 1955). The greater sweat rates attained during acclimatisation make it vital that water is replaced, so that if fluids are either not available or not consumed, it may be more beneficial to be unacclimatised. The process of acclimatisation is discussed in detail in Chapter 2.

The time course of the decay of heat acclimatisation is not clear, and is likely to be variable between individuals and environments. Pandolf (1998) cites that retention of the benefits of heat acclimation appear to remain longer for dry compared to humid heat, and that high levels of aerobic fitness seem to be associated with greater retention of heat acclimation.

1.5.2 Types of fluid replacement

When water loss replacement is accompanied by electrolyte replacement following sweating, individuals ingest more fluid and retain a higher percentage (Nose, 1988c). In fact, complete restoration of a fluid volume deficit cannot occur without electrolyte replacement (mainly sodium), either in the beverage or in food (Lassiter, 1990; Takamata et al, 1994). However, in most situations of sweat loss, the required
amount of sodium for replacement will be available in the gut from the previous meal or in the pancreatic secretions, as long as regular, balanced meals are consumed (Schedi et al, 1994). The average dietary intake of sodium in the UK is around 4 grams per day (Gregory et al, 1990), or 3.6 grams per day, with a range of 1.2 - 7.2 grams per day (Department of Health, 1994), whilst the concentration of sodium in sweat is around 0.4 - 1.2 grams/litre (Robinson & Robinson, 1954) depending upon the acclimatisation state of the individual. Therefore, to necessitate sodium supplementation would require daily sweat losses of 3 litres for an unacclimatised individual with an intake of 4 g/day of sodium, or way in excess of this if acclimatised. Electrolyte supplementation would provide more complete hydration for sweat losses greater than this, or in the absence of meals (Gonzalez-Alonso et al, 1992; Morimoto et al, 1981; Nose et al, 1988c). However, for smaller sweat losses, if sodium enhances palatability, then its presence in a replacement solution may be justified because drinking may be maximised by improving the taste qualities of the ingested fluids (Boulze et al, 1983; Engell & Hirsch, 1990) (see Section 1.5.6).

Rehydration with water taken at frequent intervals often cannot provide rates of absorption at high sweat rates (CMNR, 1994). Raising the maximum rate of liquid reabsorption would therefore be of practical benefit in limiting the dehydration that can occur over short periods. The addition of carbohydrates to a fluid replacement solution can enhance intestinal absorption of water (Gisolfi et al, 1990; Schedi et al, 1994). However, the main reason for ingesting carbohydrates with fluid replacement is to delay the fatigue that would normally be present in exercise lasting more than 1 hour without carbohydrate ingestion (Coggan & Coyle, 1991), by maintaining blood glucose levels. The value of carbohydrate supplementation in extending physical performance is usually demonstrated after 60-90 minutes of continuous activity at 60-70% maximal aerobic power (CMNR, 1994). By ingesting carbohydrates at a rate of 30-60 g/hr throughout moderate to high intensity exercise, blood glucose levels can be maintained (Coyle & Montain, 1992). This can be advantageous in that large amounts of water lost through sweating can be replaced at the same time. For example, ingesting 600-1200 ml/hr with a carbohydrate concentration of 4-8%. Carbohydrate concentrations of >10% are not advisable, as they will cause a net movement of fluid into the intestine because of their high osmolality. Little work has been carried out on the benefits of ingesting carbohydrates for work durations of less than 1 hour, and
current guidelines suggest that it is not necessary (ACSM, 1996). The carbohydrate source used does not appear to be crucial (eg. glucose, sucrose) (Leiper, 1998), but the predominant carbohydrate should not be fructose, as it is converted very slowly to blood glucose (Massicotte et al, 1989).

1.5.3 Drinking prior to physical work in the heat
Fluid replacement is believed to attenuate the increases in core temperature that accompany dehydration during exercise-heat stress by maintaining sweat and/or skin blood flow and thereby preserving the ability to dissipate heat (Coyle & Montain, 1993). In addition, it seems that the detrimental effects of work in the heat can be delayed by prior ingestion of fluid. For example, water ingested 60 minutes before exercise will enhance thermoregulation and lower heart rate during exercise (Greenleaf & Castle, 1971; Moroff & Bass, 1965). However, since this is likely to greatly increase urine production, the ingestion of 400-600 ml of water 2 hours prior to work in the heat should allow renal mechanisms sufficient time to regulate total body fluid volume (ACSM, 1996). In addition, if the time prior to work is spent in high ambient temperatures, an increase in the volume of fluid ingested may possibly compensate for the ongoing fluid losses that will occur in the 2 hours prior to work (Galloway, 1999).

1.5.4 Drinking during physical work in the heat
For maximum performance during a prolonged physical exertion in a hot and humid environment, water or fluid supplementation is essential. If it were possible to match fluid loss with an equal volume of intake, there would be little problem maintaining euhydration (Thomson et al, 1996). As previously discussed, during exercise humans do not typically drink as much water as they sweat. It is common for individuals to dehydrate by 2-6% of body weight during exercise in the heat despite the availability of adequate amounts of fluid (Greenleaf & Sargent, 1965; Greenleaf et al, 1983; Noakes, 1993; Pitts et al, 1944). However, gastrointestinal discomfort has been reported by individuals who have attempted to drink at rates equal to their sweat rates, especially in excess of 1 litre/hour (Brouns et al, 1987; Mitchell & Voss, 1991; Moses, 1990; Noakes, 1993). Since this response appears to be individual and there is no clear association between volume and symptoms, ACSM (1996) advocates that
during exercise individuals should be encouraged to consume the maximal amount of fluids that can be tolerated without gastrointestinal discomfort up to a rate equal to that lost from sweating.

Whereas there is usually no impairment of the rate at which ingested liquid reaches the stomach, several factors affect the rate at which the liquid is removed from the stomach (gastric emptying) ready for reabsorption.

The rate of gastric emptying is influenced by the volume of ingested food (Noakes et al, 1991), the caloric content, the composition and osmolality of the gastric contents, the temperature of the ingested liquid and the pH (Costill & Saltin, 1974). Other influences on the rate of gastric emptying include caffeine, emotional stress, diurnal variations, environmental conditions, menstrual cycle phase (Costill, 1990), physical exercise, individual variation, and the timing of the ingestion (Table 1.4). However, the most important factor influencing gastric emptying is the fluid volume in the stomach (Mitchell & Voss, 1991; Noakes et al, 1991; Rehrer, 1994). Most individuals can empty >1000 ml/hour when gastric fluid volume is maintained at 600 ml or more with a 4-8% carbohydrate concentration (Coyle & Montain, 1992; Noakes et al, 1991). This may be achieved by ingesting moderate (150 ml) to large (350 ml) volumes of fluid every 15-20 minutes during prolonged exercise (ACSM, 1996).

Table 1.4: Effects of solution composition on the rate of gastric emptying (Wilmore et al, 1994)

<table>
<thead>
<tr>
<th>Solute characteristics</th>
<th>Effect on the rate of gastric emptying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of solution</td>
<td>Increases with larger volumes</td>
</tr>
<tr>
<td>Caloric content</td>
<td>Decreases as the caloric density increases</td>
</tr>
<tr>
<td>Osmolality</td>
<td>Decreases with hyperosmolar solutions</td>
</tr>
<tr>
<td>Temperature</td>
<td>Cooler fluids empty faster than warm fluids</td>
</tr>
<tr>
<td>pH</td>
<td>Decreased emptying with more acid solutions</td>
</tr>
</tbody>
</table>

Exercise performed at an intensity above 70-80% maximal aerobic power is believed to reduce the rate at which gastric contents are emptied into the intestines (Costill & Saltin, 1974). Conversely, low intensity exercise actually increases the rate of emptying and shows no inhibiting features on gastric secretion (Wilmore et al, 1994).
1.5.5 Drinking following physical work in the heat

Since fluid replacement before and after exercise is unlikely to be sufficient to offset the ongoing fluid losses (Galloway, 1999), post-exercise rehydration strategies are required. In a study by Shirreffs et al (1996), individuals could not return to euhydration after the recovery period (6 hours) when they consumed a volume equivalent to, or less than, their sweat loss following exercise. This was only possible when either 150% or 200% of fluid losses were replaced. In this and another study (Maughan & Leiper, 1995), it was observed that sodium content of the rehydration solution was crucial, as the maintenance of euhydration only took place when the sodium content of the solution was >50 mmolL⁻¹.

1.5.6 Eating to enhance rehydration following physical work in the heat

It is important that fluids are available during food consumption, as most rehydration takes place during and after meals (Rothstein et al, 1947). Although eating during physical work may be restricted due to gastrointestinal discomfort, it can take place afterwards. One study (Maughan et al, 1996) assessed the rehydration effectiveness of solid food and water ingestion compared to a commercially available fluid replacement solution. Subjects were euhydrated at the end of the recovery period (5 hours after ingestion) when the solid food was consumed, whereas there was a fluid deficit of approximately 350 ml when the carbohydrate electrolyte solution was administered (body weight, urine volume and plasma volume were monitored). The authors concluded that the higher electrolyte content of the meal, which had an identical water content to the fluid replacement solution, allowed for better retention of the fluid.

1.5.7 Palatability

Enhancing palatability of fluid is one way of improving the match between fluid intake and sweat output (ACSM, 1996). Water palatability is enhanced by several factors including temperature and flavouring (Engell & Hirsch, 1990; Hubbard et al, 1984). The most pleasurable water temperature during recovery from exercise was found to be 5°C (Sandick et al, 1984), although when water was ingested in large quantities, a temperature of about 15-21°C was preferred (Boulze et al, 1983; Hubbard et al, 1984). Experiments have also demonstrated that voluntary intake is
enhanced if water is flavoured (Engell & Hirsch, 1990; Hubbard et al, 1984) and/or sweetened (Fortney et al, 1981). In general, fluid beverages that are chilled, sweetened (artificially or with sugar) and flavoured should stimulate fluid intake. Wilk & Bar-Or (1996) reconfirm the practical importance of flavour and taste as an aid to improving the willingness of individuals to rehydrate themselves adequately.

1.5.8 Provision of liquids

Supplying appropriate fluids at the required rate of demand is an important factor in the prevention of dehydration. A main point of distribution for fluids should pose no provision problems in the workplace. However, it seems that more encouragement to drink is necessary in order to prevent voluntary dehydration. This is possible in the form of personal portable fluid containers. This should be encouraged particularly when protective clothing is in use, and systems should be adapted to ease the process of drinking in this situation.

Rigid containers are often uncomfortable to carry as part of a personal load, but easy to refill, but the reverse is true for flexible containers which are also susceptible to leakage. This area has been reviewed (Thomson et al, 1996), and considers the use of existing 'sports bottles', with an ergonomic design for personal carriage and a push down drinking lid, and the bladder-type bag, with an in-built drinking tube, often commercially recognised as a 'Camelbak'.

1.5.9 Hygiene

Repeated use of commercially available carbohydrate-electrolyte drinks from the same container creates a residue that can affect the hygiene and effective function of certain water carriage devices (Nieman, 1986). Bacteria can grow in the solution, and if the solution is made dissolving powdered carbohydrates and electrolytes in water, residue can cause blockage of the container, and can lead to gastro-intestinal upset. Methods for cleaning drinking systems must be considered prior to implementing the use of such drinks.
1.6 Summary

This chapter provides an overview of the currently available information on the components, causes and effects of dehydration, in addition to methods of reducing the extent of dehydration problems. It is a basis of understanding on which to develop the experimental and theoretical work throughout the rest of the thesis. The process of acclimation can play an important part in the extent of dehydration, and for this reason, the process is explored further in Chapter 2.
Chapter 2
Chapter 2

PHYSIOLOGICAL AND BIOCHEMICAL CHANGES IN HEAT ACCLIMATION FOR SUBJECTS WITH A CONTROLLED DIET

2.1 Introduction
The aim of this chapter is to determine the extent of acclimation that will take place under controlled conditions, so that this information can be used later in the thesis to provide guidance on the benefits and drawbacks of acclimatisation in the workplace. The study will also provide the opportunity to develop a sweat sampling technique.

2.1.1 Background
In hot environments, the critical need to dissipate body heat by sweating leads to additional losses of water and water-soluble nutrients such as minerals and vitamins, and this may alter dietary requirements. The loss of high volumes of body water and nutrients is relevant to many industries where there is work and physiological adaptation in heat. Such information is vital to firefighters, military personnel, athletes, individuals working in foundries or nuclear power plants, and the construction trade. It is also important to quantify physiological changes that occur during exposure to heat when dietary requirements are not altered accordingly.

2.1.2 Sweating
It is generally accepted that human beings become adapted to a hot environment, or acclimatised, and that there are associated physiological alterations accompanying this process that can reduce the strain imposed by that environment (Wenger, 1988). A major effect of acclimatisation is that for a given heat stress, the body sweats at a greater rate and at an earlier stage, providing more sweat for greater evaporation, and hence heat loss. Sweating is initiated when the body's other channels of heat loss, such as conduction, convection and radiation, can no longer maintain heat balance. The relative humidity of a particular climate is the most important environmental factor affecting the efficiency of evaporative heat loss. The difference between the saturated vapour pressure at skin temperature and the partial vapour pressure of the air
dictates the rate at which sweat evaporates. In conditions of very high humidity, it becomes increasingly difficult to dissipate heat, as evaporation of sweat cannot take place. If sweat cannot be evaporated, it may be reabsorbed into the epidermal cells, swelling them, and blocking the orifices of the sweat ducts. The resulting process is a decreased ability to sweat, known as hidromeiosis (Kerslake, 1972).

2.1.3 Acclimatisation

By becoming acclimatised, it is possible to reduce the thermal strain imposed by extreme conditions of heat. This process occurs gradually through regular exposure to hot environments, and, depending on conditions, it takes place over 10 days or less. Methods of emulating these effects were developed some time ago by exposure to similar artificial conditions for a relatively short period on successive days. This process of acclimatisation to a different environment through artificial means is often referred to as acclimation. Fox et al (1963) showed that the degree of acclimation attained is proportional to the duration and degree to which body temperature is raised on each day of the process. Once acclimated, the thermal strain on the body is decreased by the reduction of heart rate and body temperature, both aural and rectal. Conversely, sweat rate increases in order to provide more sweat for evaporation, and hence increase dissipation of heat from dilated peripheral blood vessels. Plasma volume also increases. To date, there have been three theories advanced to explain plasma volume expansion during heat acclimation: sodium and water retention; an interplay between osmolar control and cardiovascular baroreceptor control; and protein movement from the interstitial compartment to the vasculature (Armstrong et al, 1987). Another possibility is that plasma volume may rise because more blood is needed to transfer heat to the skin. The onset of sweating occurs earlier and the volume of sweat produced is increased. The sweat itself is lower in electrolyte concentration, in order that an imbalance does not occur due to the increased volume of sweat produced (discussed in detail later). As a consequence of becoming acclimatised or acclimated, a person is able to work in a hot environment under far less physiological strain, and continue working for a considerably longer time than when not acclimatised (Bass, 1955). An unacclimatised person may experience dizziness, headaches, nausea and eventually heat illness, coma and even death under conditions that are tolerable by an acclimatised or acclimated person. Acclimation to
work in the heat is also characterised by a marked improvement in performance and comfort (Robinson & Robinson, 1954).

2.1.4 Fluid electrolyte balance

In a hot climate, rapid heat acclimatisation is critical if physical performance is to be sustained (Wenger, 1988). Heat acclimatisation increases sweat secretion and hence body sodium losses by this route. The first systematic studies of heat acclimation, conducted over 50 years ago, were followed by hundreds of others, but less than 3% of these studies controlled dietary sodium consumption or measured the impact which dietary sodium had on body fluid balance and physiological adaptations during heat acclimation (Armstrong et al, 1987). This is surprising considering the following facts: sodium is the primary cation in extracellular fluids; maintenance of intravascular and intracellular fluid-electrolyte balance is essential if exercise or physical work is to be sustained in hot environments; sodium consumption alters salt appetite and thirst; and heat disorders often represent disturbances in fluid-electrolyte balance.

Daily dietary sodium chloride recommendations for males living and working in hot environments have been published as high as 48g.d⁻¹ (Armstrong et al, 1987), which is equivalent to 19.2g of sodium; in contrast, adult males consume an average of 10-12g of sodium chloride per day in the United States, which is equivalent to 4.4g of sodium. One effect of dietary restriction of sodium is known to initiate increased secretion of aldosterone (Robinson & Robinson, 1954; Collins, 1963; Collins & Weiner, 1968), which in turn promotes maximum reabsorption of sodium by the kidney (within 6-12 hours) and the sweat gland (within 1-2 days). This increased aldosterone secretion is essential to the recovery of sodium balance in the heat acclimatisation process. However, the effects of negative or positive sodium balance and endocrine responses are beyond the scope of this chapter.

The average dietary intake of sodium in the UK is around 4 grams per day (Gregory et al, 1990), or 3.6 grams per day, with a range of 1.2 - 7.2 grams per day (Department of Health, 1994), whilst the concentration of sodium in sweat is around 0.4 - 1.2 grams/litre (Robinson & Robinson, 1954) depending upon the acclimatisation state of
the individual. Salt supplementation previously advised for hot climates (Leithead & Lind, 1964; Taylor et al, 1943) is therefore only thought necessary when excretory losses of sodium are in excess of normal intake. This would require daily sweat losses of 3 litres for an unacclimatised individual with an intake of 4 g/day of sodium, or way in excess of this if acclimatised. Clearly then, it is advantageous, in terms of sodium balance, to be fully acclimatised.

An investigation by Armstrong et al (1987) looked at the effects of high and low sodium diets during heat acclimation. They demonstrated that typical heat acclimation adaptations occurred under the influence of both high and low sodium diets, yet significant between-diet differences (heart rate, plasma protein, rectal temperature, plasma osmolality, plasma sodium, and resting plasma volume) indicated that a low sodium diet increased the risk of circulatory incompetence / heat illness during the first 6 days of exposure. Between-diet differences then decreased until they were statistically equivalent on the eighth day. There is little work available on acclimatisation with moderate sodium diets.

Following work on surfeit and deficit of sodium, Strauss put forward a model for body sodium (Simpson, 1988):

1. There is a *basal level of body sodium*, which is maintained when sodium intake is very low (just sufficient to cover obligatory losses from the skin and bowel).

2. If body sodium for any reason falls below the basal level, there is a state of *true sodium deficit*. Any ingested sodium will be retained until the deficit is made up. The evidence for this is much less, but nevertheless seems adequate (Simpson, 1988).

3. When body sodium lies above the basal level (which it usually does, since sodium is ingested daily), the body is in a state of surfeit, and the *extra sodium* (ie. the sodium in the body over and above the basal level), is in the process of being excreted.
The majority of published evidence confirms that sweat sodium concentration decreases with acclimatisation to heat (Bass et al, 1955; Dill et al, 1932). It has also been demonstrated that sweat sodium concentration increases with rate of sweating (Locke et al, 1951; Schwartz et al, 1954, 1956). Since marked increases in the rate of sweating occur during heat acclimatisation it has not always been clear to what extent observed changes in sodium concentration have been influenced by changes in sweat rate. A study by Allan & Wilson (1971) aimed to establish the effect of acclimatisation on sweat sodium concentration over a wide range of sweat rates. They compared sweat rates and sweat sodium concentration in unacclimatised and subsequently acclimatised subjects. The results confirmed that sweat sodium concentration increases with rate of sweating and decreases with acclimatisation. The acclimatisation reduction was seen over a wide range of sweat rates and appeared to be proportionally greater at higher sweat rates. From this it is clear that accounts of sweat sodium changes, or indeed other nutrients, with acclimatisation can be misleading if they are not related to stated rates of sweating. The sweat rate increases that characterise heat acclimatisation may then have given rise to underestimates of the acclimatisation reduction in sweat sodium concentration.

Apart from sodium, which has previously received detailed study, the quantitative significance of other important sweat constituents, such as potassium, still remains a matter of debate. The contribution of nutrients in sweat to overall metabolic balance has not been unequivocally settled mainly because there are conflicting data on sweat composition determined by different methods, and in few studies has there been an attempt to measure total daily losses. Further exploration is also required on the question of an adaptive sweat-gland response for the conservation of these nutrients in heat acclimatisation.

When we are in daily sodium and potassium balance, which applies to most of us most of the time, what goes in must come out. Variable, but usually small amounts are lost via the skin, and very tiny amounts are lost in the faeces. Thus, the kidneys are the main route of excretion of sodium and potassium. However, during periods of intense heat stress, and particularly when considerable physical effort is being exerted, sweat rate greatly increases and much more of these nutrients than normal are lost via the skin. A study by Collins et al (1971) on an ocean-going sea tanker looked at
nutrient balance during heat acclimatisation. Between the meals on a set menu, subjects could snack, and they could add table salt to their meals ad libitum. They concluded that sodium and potassium concentrations in sweat are not altered by acclimatisation to heat when dietary intake is adequate to balance sweat losses of up to 4.0 litres/day. However, it is not always the case that increased salt intake is available, sought, or indeed that subjects are well enough informed that they should replace lost nutrients.

2.1.1 Functions and Regulation of Electrolytes

Sodium is necessary for the transmission of impulses in nervous and muscle tissue. Being the most abundant extracellular ion, its location and concentration also play a significant role in fluid and electrolyte balance. The sodium level in the blood is controlled primarily by the hormone aldosterone from the adrenal cortex. Aldosterone acts on the distal convoluted tubules of the nephron of the kidneys and causes them to increase their reabsorption of sodium. The sodium thus moves from the filtrate back into the blood and establishes an osmotic gradient with the result being that water follows, moving from the filtrate back into the blood. Although the body can reduce the amount of sodium lost in urine to zero, this may not always be sufficient to compensate for excessive sodium loss in sweat. Mild sodium deficiency can result in muscle cramps after a few hours of work or exercise in the heat. However, severe sodium deficiency can have profound effects on the body: fall in blood pressure, tiredness, nausea, dizziness and shock. If thirst is satisfied with water, or other salt-free drink, body fluids are diluted and this results in mental confusion, convulsions and coma.

Potassium is the most abundant cation in intracellular fluid. It assumes a key role in the functioning of nervous and muscle tissue and abnormal blood potassium levels adversely affect neuromuscular and cardiac function. Potassium also helps maintain fluid volume in cells. The blood level of potassium is under the control of mineralocorticoids, mainly aldosterone. The mechanism is exactly opposite to that of sodium. When sodium concentration is low, aldosterone secretion increases, and more sodium is reabsorbed. But when potassium concentration is high, more aldosterone is secreted and more potassium is excreted. Symptoms of a lower than
normal level of potassium include: cramps, fatigue, nausea, vomiting, shallow respirations and mental confusion.

2.1.6 Aims of the study
The first aim of this study was to review acclimatisation. The second aim was to quantify physiological changes in the body, and therefore the extent of acclimation, during the initial days of exposure to heat when the dietary intake of sodium before and during the exposure to heat was a strictly controlled moderate amount. A further aim was to develop a sweat sampling technique for use in subsequent studies.

2.2 Method
2.2.1 Subjects
Four healthy, male volunteer subjects were recruited from the undergraduate population at Loughborough University. They were fully informed of the aims and procedures of the study. Subjects completed the Human Thermal Environments Laboratory (HTEL) Loughborough University health screen questionnaire (Appendix I), before written informed consent was obtained. The study was approved by the Loughborough University Ethical Advisory Committee (G97/6). The experiment was carried out at the same time every day to control for circadian rhythm effects. The subjects were unacclimatised to heat and therefore the experiments were carried out during the winter / spring months. The subjects were not sportsmen that took part in regular endurance training.

Several days prior to testing, subjects were familiarised with the laboratory, the heat chamber (not in the heat), and the test procedures. At this time, anthropometric measurements of height, weight and percentage of body fat were taken, and subject age was also noted. The mean values (± SD) were: height of 179.2 ± 3.1 cm; weight of 82.89 ± 6.87 kg; age of 20.3 ± 1.7 years, and percent body fat of 17.0 ± 5.4 %.

Subject height was measured using a stadiometer. Subjects stood erect against the measuring pole, and their heads were positioned so that the Frankfurt plane was horizontal. Accuracy of measurement was 0.1 cm. Weight was determined using a weighing platform (Mettler ID1 multi-range, order code ID1s, Albstadt, Germany,
accurate to ± 1 gram). Subjects were asked to stand in the middle of the platform with feet shoulder width apart, to focus on a point directly ahead of them and to remain as still as possible throughout the measurement. A dynamic average measurement was taken over 9 seconds. During the experiment, subjects were weighed in their underclothes before (Sb) and after (Sa) each exposure. Their clothing was also weighed before (Cb) and after (Ca) each exposure. The following can be determined from this information (adapted from Parsons, 1993):

Total sweat loss from the body (Swi) = Sb - Sa  \hspace{1cm} (Eq. 2.1)

Sweat trapped in clothing (Swt,) = Ca - Cb \hspace{1cm} (Eq. 2.2)

Sweat evaporated (Sw_{evap}) = Sw_{i} - Sw_{tr} \hspace{1cm} (Eq. 2.3)

Body fat was measured using the following procedure: skinfold callipers (Bi-Harpenden skinfold callipers, John Bull, British Indicators Ltd, England) were used to measure skinfolds at four sites (Tanner & Whitehouse, 1955) three times and an average was taken. The four sites were: biceps, triceps, suprailiac and subscapular. Skinfolds were then used to calculate the body fat percent of the subjects according to the methods of Durnin & Rahaman (1967), Womersley & Durnin, (1974) and Siri (1956). The following equations were used:

**Body density regression equations:**

Male age 17-19 \hspace{1cm} y = 1.1620 - 0.0630x \hspace{1cm} (Eq. 2.4)

Male age 20-29 \hspace{1cm} y = 1.1631 - 0.0632x \hspace{1cm} (Eq. 2.5)

Male age 30-39 \hspace{1cm} y = 1.1422 - 0.0544x \hspace{1cm} (Eq. 2.6)

where \( y = \) density, and \( x = \log \Sigma \) fats

**Body fat percentage:**

\[
% \text{ body fat} = \left( \frac{4.95}{D - 4.5} \right) \times 100 \hspace{1cm} (Eq. 2.7)
\]

2.2.2 Organisation of the study

The study was conducted in two experimental trials, each lasting five days. The experimental work was carried out over approximately three hours on each of the five days. The exercise bouts were conducted at the same time each day.
Two pilot studies were carried out in order that: 1) the suitability of the sweat collection capsules could be tested, and appropriate modifications made; 2) to ascertain how regularly the sweat capsules needed to be replaced during the experiment; 3) sweat could be analysed, to ensure that sodium and potassium are the most important ions to be considered; and 4) to practice the skill of sweat analysis. Each of the pilot trials lasted only one day, and there were 2 weeks between each of them and the actual study to prevent early acclimation.

2.2.3 Measuring equipment
Subject internal body temperature was measured using aural thermistors (Grant Instruments Ltd, Cambridge, UK, Model: EAR-U), which were embedded in acrylic ear pieces, positioned in the right and the left ears to give mean aural temperature ($T_{au}$). The ear pieces were placed in the ear so that the sensors were located in the external auditory meatus, close to the tympanum, which reflects the temperature of the blood in the internal carotid artery (the blood vessel that supplies the hypothalamus, the centre for thermoregulation in the brain). In order to prevent temperature readings recording that of the external environment and to avoid conduction of heat down wires, it was necessary to insulate the sensors. This took the form of cotton wool pads with tape (Transpore™), which also helped keep the sensor in position, and adjustable ear defenders (Bilsom, Model No: 2452). An average value was produced from the right and left ear measurements to give internal body, in this case aural, temperature ($T_{au}$).

Subject skin temperature was measured by placing flat plate copper thermistors (Grant Instruments Ltd, Cambridge, UK, Model: EUS-U) on the skin, held in place with vapour permeable tape (Transpore™). An estimate of mean skin temperature ($T_{sk}$) was calculated from weighted average measurements at four specific points on the skin, according to the method of Ramanathan (1964). The weighting coefficients used in the formula to calculate the estimate of mean skin temperature are shown in Table 2.1. It was considered that the skin temperature would be homogenous due to vasodilation, and therefore four points were sufficient to represent $T_{sk}$.
Table 2.1: Weighting coefficients used to calculate mean skin temperature (T<sub>sk</sub>)

<table>
<thead>
<tr>
<th>Temperature measurement site</th>
<th>Weighting coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left upper chest</td>
<td>0.3</td>
</tr>
<tr>
<td>Left front shoulder</td>
<td>0.3</td>
</tr>
<tr>
<td>Right anterior thigh</td>
<td>0.2</td>
</tr>
<tr>
<td>Right shin</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Aural and skin temperature data were stored every minute in an 8-bit squirrel data logger (Grant Instruments Ltd, Cambridge, UK, Model: SQ32-160). Manual recordings of these temperatures were taken every 5 minutes throughout the experiment as back up.

Subject heart rate (HR) (beats per minute) was measured using a heart rate sensor comprising of electrodes strapped around the chest, which transmits radio signals to a watch worn on the wrist (Polar Sports Tester, Cranlea Medical Electronics, Birmingham, UK, Model: PE 4000). In order that interference of signals should be limited, subjects did not wear their own watches and remained at least 1 metre apart throughout the experiment. Manual recordings of HR were taken every 5 minutes throughout the experiment as back up.

Prior to and following the pilot trials and each experimental day, all skin and aural thermistors were calibrated across the expected range of use (35 – 39 °C) against two mercury-in-glass thermometers (Boots PLC, Nottingham, UK) in a water bath (Grant Instruments Ltd, Cambridge, UK, Model: SE 15). Only those that fell within ± 0.1°C of the thermometers (which gave the same readings) were used. All data loggers had at least 100 battery days remaining each time experimental work commenced. New batteries were put in the heart rate sensors prior to experimental work.

2.2.4 Sweat collection capsules

The sweat collection capsules were designed specifically for this experiment. Sweat was absorbed on squares (different sizes for pilots and full trial) of Whatman 4 Qualitative 11.0cm filter paper. The filter paper was held in place by patches made of polythene and Transpore<sup>TM</sup> tape. It was considered that the capsules did not encourage more or less sweating on these sites than on the rest of the body, as they
were ventilated with the regular replacement of filter paper squares, and the Transpore™ tape was vapour permeable. Sealable polythene bags were prepared for the immediate transfer of soaked filter papers from the skin, in order to prevent evaporation. Latex gloves (Bodyguards, Spalding, Lincolnshire, UK, Code No. BM 8001) were worn by the experimenter and tweezers were used to handle the filter paper in order to prevent contamination. The sweat collection capsules were attached at eight sites over the body, as shown in Figure 2.1

![Sweat collection patch sites](image.png)

**Figure 2.1:** Sweat collection patch sites

### 2.2.1 Diet

A strictly controlled diet was necessary in order to control for any trend in sodium and potassium secretion in the sweat. A diet was designed which comprised as closely as
possible the recommended daily amounts (RDA) for food, energy and nutrients for an adult male in the UK (Bender, 1986; Department of Health, 1989, 1992; ILEA, 1985; Ministry of Agriculture, Fisheries and Food, 1992; Salmon, 1991). The subjects ate the same menu of food as each other (corrected for subject weight), and ate the same menu every day. They were not permitted to eat anything extra, or leave any of the food they were provided with. Subjects had to drink at least 4 litres of water per day. They were not permitted any alcohol, caffeine, or added salt or sugar. Subjects’ diets were controlled for two days prior to the start of the experiment and every day throughout.

2.2.6 Pilot Trial I

The climatic chamber was maintained at (mean ± SD): $T_s = 40.9 \pm 1.2 \, ^\circ C$ and $rh = 42 \pm 0.8 \%$ (intended conditions: $40 \, ^\circ C$ $T_s$ and $40\%$ rh). This hot-dry environment was chosen to reduce the risk of sweat dripping from the skin and the effects of hidromeiosis on sweat production.

Subjects were weighed semi-nude and their clothing was weighed separately so that sweat held in clothing could be accounted for. Subjects were clad in cotton underpants, cotton shorts, cotton-rich socks and training shoes, and asked to sit in a thermally neutral room. Heart rate monitors, thermistors and data loggers were then attached to the subjects. The sweat collection capsules were placed on the subjects directly before entering the environmental chamber, as tape does not adhere to the skin sufficiently once sweating has commenced.

Subjects entered the environmental chamber and sat at rest for 10 minutes. The filter paper squares, which had sides of 2 cm for this pilot trial, were inserted into the sweat collection capsules. Subjects then performed a standardised stepping exercise task for 10 minutes. They stepped onto a 22.5 cm block at a rate of 12 steps per minute in time to an electronic metronome, equivalent to approximately 172 W/m². After 10 minutes of stepping, subjects stood at rest while the filter paper in each sweat collection capsule was removed and replaced, and a further 10 minutes of stepping commenced. Subjects performed four sets of 10 minute steps. The filter papers from
all four stepping sessions were transferred to the same sealable polythene bag for each subject. Subjects were not allowed to drink throughout the heat exposure.

At the end of the stepping exercise task, subjects' thermistors and heart rate monitors were removed, and they exited the chamber. Subjects were reweighed semi-nude, and their clothing was also reweighed.

2.2.7 Pilot Trial 2

The procedure for the second pilot trial was the same as for the first, except for the following points:

a) The environmental conditions in the thermal chamber were changed from \( t_a = 40^\circ C \) and \( r_h = 40\% \) to \( t_a = 45^\circ C \) and \( r_h = 30\% \) (actual environmental parameters: (mean ± SD) 45.3 ± 0.6 °C \( t_a \) and 31.1 ± 0.8 % \( r_h \)). Temperature was increased in order to create a better gradient between the saturated vapour pressure on the skin and the partial vapour pressure in the air. A relative humidity of 30% was selected to make sweating easier through increased evaporation from the skin.

b) Subjects showered directly before they entered the chamber to eliminate any sweat produced before experimentation began.

c) Subjects wore only underpants and shorts, with no socks and training shoes, which collected sweat that otherwise could have evaporated in the first pilot trial.

d) Filter paper size in the sweat collection capsules was changed from 2cm to 4cm.

e) The filter papers from each of the four stepping sessions were placed in separate sealable bags so that analysis of sweat could take place over the exercise bout, as well as over the 5 days of the experiment.

f) The rate of stepping dictated by the metronome changed from 12 to 15 steps per minute, equivalent to approximately 216 W/m², to increase exercise and sweat rate.
f) The rate of stepping dictated by the metronome changed from 12 to **15 steps per minute**, equivalent to approximately 216 W/m², to increase exercise and sweat rate.

g) Weighing scales were taken into the chamber, and all weighing took place in there. Subjects were weighed every time a sweat collection capsule was replaced, so weight loss throughout the whole exercise bout could be observed. Therefore, subject weights included equipment.

h) Music was provided to prevent monotony, although not so loud as to interfere with the audibility of the metronome.

### 2.2.8 The Full Study

The procedure for the full study was the same as for the second pilot trial, except for the following points:

a) The environmental conditions in the thermal chamber were changed from $t_s = 45^\circ\text{C}$ and $rh = 30\%$ to $T_s = 45^\circ\text{C}$ and $rh = 40\%$ (actual environmental parameters: (mean ± SD) $44.8 \pm 0.5^\circ\text{C}$ $T_s$ and $41.6 \pm 1.1 \%$ rh). The humidity was increased because subjects complained that the environment was too dry and gave them sore throats and skin rashes. Air velocity ($v$) was also measured in the full study, and was (mean ± SD) $0.24 \pm 0.07 \text{ m s}^{-1}$.

b) A **15 minute cycle** period was added to the program before stepping began in order to encourage the subjects sweat more and earlier.

### 2.2.9 Subjective Measures

Subjective measures were taken only in the full study. Before the cycle period and after the cycle period and each stepping session (six occasions each day) subjects were requested to indicate their thermal sensation on five sensation scales (ASHRAE, 1966; ISO 7730, 1992). These were for thermal sensation at the head, trunk, arm and leg regions, and finally an overall thermal sensation rating. The scale used for each area of the body is shown in *Figure 2.2*. Subjects were asked to make a horizontal
mark across the vertical line of the scale in the place that represented their thermal sensation.

+4 Very hot
+3 Hot
+2 Warm
+1 Slightly Warm
0 Neutral
-1 Slightly Cool
-2 Cool
-3 Cold
-4 Very Cold

*Figure 2.2: Thermal sensation scale*

**2.2.10 Sweat Analysis**

After the capsule assemblies were dismantled, each set of filter papers was weighed. They were then analysed for presence of sodium and potassium using the flame photometry method.

Each set of filter papers was placed into a beaker containing 0.01M hydrochloric acid (HCl) and pulped. A solution (500 ppm sodium, 500 ppm potassium) was made up in order to create standard solutions against which the sweat samples could be compared. The standards were made up by adding decreasing parts of the solution and increasing parts of distilled water. Calibration curves were made for the standards. After centrifugation, the sodium and potassium content of the supernatant liquid from each sample was derived using a flame photometer (Jenway Flame Photometer) with the suitable standards. Plain, dry filter paper was also pulped and analysed to ensure any sodium or potassium present before sweat absorption could be accounted for.

Exactly the same procedure was used for all the samples, and each sample was analysed in triplicate. All solution measures were made using pipettes and winders. The work took place in the Analytical Division of the Chemistry Department at
Loughborough University. Although this is not an industrial setting, the standards of NAMAS (National Analytical Measurement Accreditation Service) and GLP (Good Laboratory Practice) are adhered to when technical checks are made.

2.2.11 Statistics

The Student’s t-test was used to determine changes over the period of acclimatisation. Significance was determined at the $p < .05$ confidence level and where the Bonferroni correction was applied, the significance will be denoted thus: $p^b < .05$. The Bonferroni correction adjusts the observed significance level for the fact that multiple comparisons are made. Therefore, where three comparisons are made, for example, the significance level, $p < .05$, will be divided by three, to give $p < .016$. All terms were expressed as the mean ± SD

2.3 Results

2.3.1 Aural temperature

There were significant reductions ($p^b < .05$) in $T_{au}$ at the end of Exercise 1 and Exercise 5, between Days 1 and 5 (Table 2.2). Individual $T_{au}$ responses are shown in Figure 2.3. There were clear inter-individual differences in $T_{au}$ response, whereby Subject 2 maintained the lowest $T_{au}$, and Subject 4 the highest, at any given time.

Table 2.2: Mean (±SD) values at the end of the 1st and the 5th exercise sessions on each day

<table>
<thead>
<tr>
<th>Day</th>
<th>$T_{au}$ (mean±SD)</th>
<th>$T_{sk}$ (mean±SD)</th>
<th>HR (mean±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>End Ex 1</td>
<td>End Ex 5</td>
<td>End Ex 1</td>
</tr>
<tr>
<td>1</td>
<td>37.5 ± 0.1</td>
<td>38.8 ± 0.5</td>
<td>37.0 ± 0.5</td>
</tr>
<tr>
<td>2</td>
<td>37.2 ± 0.2</td>
<td>38.7 ± 0.4</td>
<td>37.5 ± 0.3</td>
</tr>
<tr>
<td>3</td>
<td>37.1 ± 0.1</td>
<td>38.6 ± 0.4</td>
<td>37.8 ± 0.3</td>
</tr>
<tr>
<td>4</td>
<td>37.1 ± 0.3</td>
<td>38.5 ± 0.3</td>
<td>38.0 ± 0.2</td>
</tr>
<tr>
<td>5</td>
<td>37.0 ± 0.4*</td>
<td>38.3 ± 0.3*</td>
<td>37.9 ± 0.3*</td>
</tr>
</tbody>
</table>

* $p^b < .05$ for comparison of Days 1 & 5  

2.3.2 Mean skin temperature

At the end of Exercise 1, $T_{sk}$ increased significantly ($p^b < .05$) between Days 1 and 5 (Table 2.2). $T_{sk}$ also increased significantly ($p^b < .05$) at the end of Exercise 5, between Days 1 and 5 (Table 2.2). Individual $T_{sk}$ responses are shown in Figure 2.4.
There was a significant attenuation ($p < .05$) in HR at the end of Exercise 5 between Days 1 and 5 (no comparison was made for the end of Exercise 1), as shown in Table 2.2. Individual HR responses are shown in Figure 2.5.

### 2.3.3 Heart rate

There was a significant attenuation ($p < .05$) in HR at the end of Exercise 5 between Days 1 and 5 (no comparison was made for the end of Exercise 1), as shown in Table 2.2. Individual HR responses are shown in Figure 2.5.
2.3.4 Sweat rate

Daily sweat rate increased significantly ($p < .05$) between Days 1 and 5, (Figure 2.6). There was a mean increase in sweating response of 25% over the five day acclimation period. Sweat rate also increased significantly ($p < .05$) within each day (sweat rate during Exercise 1 compared to Exercise 5), except for Day 1 (Figure 2.6). Individual sweat rate increases over the acclimation period are shown in Figure 2.7.
2.3.5 Percentage of sodium in original sweat sample

Daily sweat sodium concentration decreased significantly \( (p < .05) \) between Days 1 and 5 (Figure 2.8). However, sweat sodium increased within each day, although not significantly. Mean daily sodium concentration in the samples decreased by 40.9% of the original sample between Days 1 and 5. The largest decrease in mean daily sodium concentration was 18.1% between Days 3 and 4, and the level did not decrease on Day 5 (1.2% increase). This created a 'step' effect, so that output did not continue to decrease after Day 4.

Figure 2.7: Individual total daily sweat rates

Figure 2.8: Change in mean sweat sodium concentration, within and between days
2.3.6 Percentage of potassium in original sweat sample

Daily sweat potassium concentration decreased significantly \((p < .05)\) between Days 1 and 5, although the level fluctuated during that time (Figure 2.9). There were no significant changes within days for sweat potassium. Mean daily potassium concentration decreased by 31.4% of the original sweat sample between Days 1 and 5. The largest decrease in mean daily potassium output was 34.7% between Days 3 and 4. Again, a 'step' effect was created, where output decreased by a large amount, but then remained at a similar level.

2.3.7 Relationships between sweat rate and sodium and potassium

Sweat rate was plotted against sweat sodium for Days 1 (unacclimatised) and 5 (acclimatised), to assess the effects of both increased sweat rate and acclimation on sweat sodium (Figure 2.10). Although the regression lines are not significant, there is a clear trend of increased sweat sodium with increased sweat rates, and lower sweat sodium content after acclimation.

![Figure 2.9: Change in mean sweat potassium concentration, within and between days](image)

The same graph was plotted for sweat potassium (Figure 2.11), which shows an increase in sweat potassium with increased sweat rates, and a decrease in sweat potassium after acclimation, the difference being larger at higher sweat rates. However, there were large inter-individual differences in sweat rate, sweat sodium and sweat potassium, and there are insufficient data to draw firm conclusions.
2.3.8 Thermal sensation

There were no significant differences in the perception of thermal sensation by the end of the exposure on Day 1 compared to the end of Day 5 ('very hot'). However, it took significantly more time ($p < .05$) for subjects to feel 'very hot' on Day 5 than it did on Day 1: all subjects felt 'very hot' during Exercise 2 (and from there onwards) on Day 1, but it took until Exercise 4 for three subjects, and Exercise 5 for all subjects to feel 'very hot' on Day 5.
2.4 Discussion

The specific objectives of this study were, in addition to reviewing acclimation, to determine the extent of acclimatisation during the initial days of exposure to heat when the dietary intake of sodium before and during the exposure to heat was a strictly controlled moderate amount. A further aim was to develop a sweat sampling technique to provide information within and between heat exposures.

2.4.1 Aural Temperature

It has been suggested that acclimation lowers the thermostatic setting of the brain, thus enlarging the body’s capacity for coping with excessive heat (Wenger, 1988). Since $T_{au}$ at the end of Exercise 1 decreased significantly ($p^b < .05$) from Day 1 to Day 5, this may have been the case. Thermal strain was reduced over the five day period, as there was also a significant decrease ($p^b < .05$) in $T_{au}$ at the end of Exercise 5 between Days 1 and 5. Bass (1955) showed that as a consequence of becoming acclimated, a person is able to work in a hot environment under far less physiological strain, and continue working for a considerably longer time than when not acclimated. So it would seem that even a five day heat sojourn is beneficial in lowering temperature for work in the heat.

2.4.2 Mean Skin Temperature

During acclimatisation, as was the case in this study, sweat rate increases in order to provide more sweat for evaporation, and hence increase heat dissipation from dilated blood vessels. There was a significant rise ($p^b < .05$) in $T_{sk}$ at the end of Exercise 1 between Days 1 and 5, indicating the onset of an earlier sweating response. $T_{sk}$ was also significantly higher ($p^b < .05$) on Day 5 than Day 1, following Exercise 5, contributing to a lower core temperature, and thus thermal strain. Previous studies which have shown a decrease in $T_{sk}$ have been conducted in less harsh thermal environments, with lower temperatures and humidities (Armstrong et al, 1987).

2.4.3 Heart Rate

There was a significant reduction ($p < .05$) in heart rate at the end the heat exposure on Day 5 compared to Day 1. This is consistent with the findings of many studies where subjects were acclimated (Allan & Wilson, 1971; Armstrong et al, 1987;
Collins et al, 1971). These decreases in heart rate could be due to a number of influences: subjects’ apprehension about the experiment may have been reduced as they became more familiar with procedures; secondly, the reductions in heart rate may have been a direct effect of the acclimation process; and thirdly, aerobic training effects may have led to lower heart rates this may also have contributed to lower $T_{an}$. Since the acclimation period was relatively short in comparison to some studies, and the aerobic demands of this study were not especially high, a combination of the these influences is likely to be responsible for reduced heart rates over the experiment.

2.4.4 Sweat Loss

The significant increase in sweat rate, in addition to the decrease in $T_{an}$ and HR, demonstrates that a degree of heat acclimation was achieved, although other studies have found substantially higher increases in sweat rate of 70% (Allan & Wilson, 1971) and 100% (Fox et al, 1963). Subjects began to produce more sweat earlier in the session as the days progressed. These results are in accordance with a study by Allan & Wilson (1971), who confirmed a substantial degree of heat acclimation in their subjects. It is, however, likely that a further increase in sweating response would have been achieved by a more prolonged period of acclimation, since increases in the region of 100% have been described (Fox et al, 1963). It seems that when investigating sweat loss in such conditions, it is important to consider individual differences, as in this study, one subject’s lowest daily sweat loss was greater than the other three subjects’ largest daily sweat losses. Therefore, when considering issues of fluid replacement, relative increases in sweat loss should be taken into account more readily than actual increases.

2.4.5 Sodium in sweat samples

Within days, the concentration of sodium in sweat increased (between the first and last sweat samples), yet between days, the concentration of sodium decreased. The study by Allan & Wilson (1971) showed that sweat sodium concentration increases with rate of sweating and decreases with acclimation. Here, the same pattern has been observed: as rate of sweating increases throughout a day, so does sodium output. However, as subjects become acclimated over the week, sodium output falls. The following may be an explanation of observed changes. It is a usually accepted theory
that sodium is reabsorbed from the sweat, after secretion, during its passage down the sweat duct and that the rate of sodium reabsorption has a maximum limit. Thus, at high sweat rates there is insufficient time for sodium reabsorption, and the concentration of sodium in the sweat at the duct outlet therefore rises with increasing rates of sweating (Bulmer & Forwell, 1956). On this basis, increasing sweat production in the secretory portion of the gland after heat acclimation would lead to a more rapid passage of sweat down the duct and, hence, a rise in sodium concentration, contrary to this study's observations. It would therefore be necessary to suggest that the capacity for sodium reabsorption is increased after acclimation, possibly through the action of aldosterone, and to a degree that proportionally matches the increase in sweat production.

These findings were contrary to those of Collins et al (1971), who found no evidence to show that whole body sweat concentration of sodium (and potassium) was altered by adaptation to heat. However, in this study, subjects were allowed to choose their own food, and encouraged to add salt to it. This suggests that when people are made aware of the importance of nutrient replenishment, and also have access to it, they will consume adequate amounts in order that the body can remain in balance, even with sweat loss. However, when dietary sodium is restricted for some reason, a basal level of body sodium may be maintained, as put forward by Strauss (Simpson, 1988). The 'step' effect created would support this theory, as by Day 4 sodium output in sweat decreased markedly, and remained at this level until the end of the experiment. However, since significant physiological changes took place that constitute acclimation to a degree, it seems that consuming a moderate sodium diet was sufficient. Also, in non-experimental conditions, individuals may well adapt their food choices or add salt to their food, as in the Collins et al (1971) study.

2.4.6 Potassium in sweat samples

Potassium concentration in sweat decreased significantly (p < .05) between Days 1 and 5, and also produced a 'step' effect. The restriction of potassium output from Day 4 onwards demonstrates that the body is aware of the depletion of a nutrient that plays a key role in the functioning of nervous and muscle tissue. As with sodium, these findings were contrary to those of Collins et al (1971), who found no evidence
to show that whole body concentrations of sweat potassium were altered by acclimation to heat.

2.4.7 Thermal Sensation
Subjective indications were that subjects took longer to feel hotter under the same conditions, which reflects that found by Robinson & Robinson (1954): that acclimation to work in the heat is characterised by a marked improvement in comfort.

2.4.8 Sweat electrolyte collection technique
The method used took samples from eight sites over the body. The sweat collection patches were considered to be regularly aerated, although not to the normal extent, and this method allowed a comparison of change in sweat electrolytes throughout each session, as well as over the five days. For studies aiming to balance electrolyte gains and losses, a more appropriate collection technique would be a whole body wash-down.

2.5 Conclusions

- The consumption of a controlled, moderate salt diet allowed some acclimation to be achieved, thereby reducing thermal strain (significantly lower Taw, HR and greater sweat rates).

- The concentration of sodium and potassium in sweat increased with sweat rate and decreased with acclimation. On Day 4, output levels of sodium and potassium were markedly reduced, probably as a result of the acclimation induced increase in sweat rate.

- The sweat electrolyte collection technique allowed comparison throughout heat sojourns, as well as between them.

- The greater sweat rates produced at the end of the acclimation period in this study allow comparisons to be made to work situations, where there will be both benefits and potential drawbacks. Benefits in terms of the reduced physiological strain for
for the same given situation, but a possible drawback in that greater sweat rates will increase the likelihood of heat related illness if a person is not made aware of the need to consume more fluids than they did previously.

- Acclimation (or acclimatisation if naturally occurring) clearly has a potentially large part to play in dehydration, which allows cautionary guidance to be provided later in the thesis. What is now required are methods for determining the extent of dehydration when it occurs, in order to control the adverse effects.

2.6 Summary of Part I

- Chapter 1 provided a general introduction to dehydration: its components, how it occurs, its effects, and how to avoid or reduce it. This information comes from the many studies that have been carried out in this area, and provides a basis of understanding for the work presented in the rest of the thesis.

- Since acclimation can form a large part in the extent of dehydration that can take place, a study was carried out in Chapter 2 that determined whether it would take place over a short period of time. This was found to be the case, and has allowed guidance to be provided later in the thesis.

- The next part of the thesis will address methods of determining the extent of dehydration, so that they may be applied in field and laboratory settings.
Part II

Methods of Assessing
Hydration State
This section of the thesis aims to consider and evaluate various methods of determining and/or controlling human hydration state for use in the remaining part of the thesis.

Chapter 3 discusses thirst, one of the fundamental aspects of dehydration. Is thirst a sufficient stimulus for people to drink adequate amounts of fluid, and therefore suitable to be relied upon as a method for controlling hydration state? The accuracy and practicality of other measures of hydration state are studied in Chapter 4, including urinary, haematological and sweat measures. This work provides the basis for subsequent fieldwork and laboratory studies. An additional technique for analysing body water changes, called bio-electrical impedance analysis (BIA), is investigated in Chapter 5.
Chapter 3
Chapter 3

THE SENSATION OF THIRST

My strength is dried up like a potsherd; and my tongue cleaveth to my jaws; and thou hast brought me into the dust of death.

(Psalms 22: 15)

3.1 Introduction

When considering dehydration, one of the most closely related sensations is that of thirst, arising from lack of body water. In resting humans there normally is a continuous loss of water from the respiratory tract and skin to the environment, and an intermittent loss of water and electrolytes from the gastrointestinal tract and the kidneys. This process is expedited by the loss of water and electrolytes at the sweat glands during heat stress and / or exercise. Humans replace such lost water and electrolytes by consuming food and drink. The body’s solute composition and the volume of the extracellular fluid are maintained in dynamic balance and partially controlled by antidiuretic hormone and thirst (Andersson, 1978).

This chapter aims to define thirst in terms of psychological and physiological responses and determine how such responses can be measured. The concept of voluntary dehydration, which occurs when sufficient fluids are available but not consumed, shall be addressed, as will the reasons for it taking place. This information will allow judgements to be made regarding the suitability of thirst as a sole indicator of the need to intake fluids, and the need for other measures or indicators of hydration state.

3.2 The definition of thirst

Thirst can be defined as:

‘That condition of mind which elicits a desire to drink in order to alleviate a sensation of dryness in the mouth and throat’ (Parsons, 2000).

Greenleaf (1992) cites an appropriate physiological definition as being one that includes a desire to drink resulting from a deficit of water. The sensation of thirst was summarised by Rolls & Rolls (1982a):
"Thirst is a subjective sensation aroused by a lack of water. As a powerful and compelling sensation, it is perhaps only exceeded by the hunger for air and by pain. Associated with the sensation of thirst is the desire to drink water, and usually thirsty subjects report a dry feeling in the mouth and find that water tastes pleasant."

The essence of that quote is the reasoning behind this chapter: at extreme levels of hypohydration, the sensation of thirst may be powerful, but research suggests that at less extreme levels, it is a poor indicator of the body's need for water and electrolytes. Most non-social drinking is stimulated by the sensation of thirst. There are a wide variety of causes of thirst but the most documented aspects are those concerning water loss through combinations of exercise heat stress and water deprivation. Rolls & Rolls (1982b) list some other possible causes, including certain foods and psychological factors.

3.3 The measurement of thirst

There is a vast quantity of literature and research documenting the detrimental effects of body water deficit, and it is rare to read any of this literature without finding some reference to the work of Adolph and colleagues in the desert environment. They carried out research over a number of years concerning the heat strain and hydration levels of soldiers working in the desert heat. They found that at 1% body weight loss, thirst was initiated and went on to document further detrimental effects of body weight loss resulting in death if water was not administered (Adolph, 1947; Rothstein et al., 1947). The list of detrimental effects, both physiological and psychological, caused by progressive dehydration has been confirmed and refined by many other researchers, and is shown in Table 1.2. Thirst was once considered to be an 'all or nothing' sensation, but research now indicates that the response can be graded (Nadel et al., 1993), as shown in Table 1.2, where 2% body weight loss elicits a stronger thirst than 1%.

Although the physiological responses to a water imbalance have been extensively studied, there is little documented evidence regarding the subjective sensations associated with thirst. Such studies tend to note at which point the sensation of thirst
occurred, and consequently associate the onset with a percentage of body weight loss. Rolls et al (1980) investigated quantitatively not only the sensation of thirst, but also other associated sensations. Following 24 hour water deprivation, human subjects were asked to respond to the question ‘How thirsty do you feel now?’ by marking the position corresponding to their sensation on a 100 mm line, as shown in Figure 3.1. Other questions asked of the subjects included: ‘How dry does your mouth feel now?’ (not at all – very dry); ‘How would you describe the taste in your mouth?’ (normal – very unpleasant); How pleasant would it be to drink some water now?’ (very pleasant – very unpleasant); and ‘How full does your stomach feel now?’ (not at all – very full).

How thirsty do you feel now?

[———]

Not at all Very thirsty

Figure 3.1: An example of a visual analogue rating scale used by human subjects to provide a measure of thirst. The 100 mm line was marked at the position which corresponded to the degree of thirst felt (Rolls et al, 1980)

Other studies have used similar methods of quantitatively measuring perceived level of thirst and stomach fullness (Meyer et al, 1994; Phillips et al, 1983; Wilk & Bar-Or, 1996).

3.4 How is thirst initiated?

Commonly associated with thirst is a dry mouth. Cannon (1918) suggested that a dry mouth causes drinking behaviour in humans, as we avoid the disagreeable sensations that arise from the salivary glands lacking the water they need to function properly. Although the consistency and flow of saliva are an important part of the stimulus to drink, they proved not to be essential factors in initiating drinking behaviour in humans: people who have a congenital lack of salivary glands do not exhibit increased fluid consumption and appear to have normal water and salt metabolism (Steggerda, 1936; 1941). However, several studies have shown that dehydration of the oropharyngeal cavity is a predominant physiological stimulus in influencing thirst.
Changes in plasma osmolality and volume have been also demonstrated to be key factors in initiating thirst.

Changes in the volume of liquid ingested and urine produced are controlled by thirst and the ADH plasma level respectively. Both thirst and the plasma level of ADH are controlled by centres in the hypothalamus, which are stimulated by two changes in the plasma: increased plasma osmolality and decreased plasma volume.

**Increased plasma osmolality** - The hypothalamic osmoreceptors that monitor the ECF's osmolality provide the input to both the thirst centre and the ADH-secreting cells. The osmoreceptors respond to increases in plasma osmolality produced by either a deficit of total body water or a predominance of extracellular solutes. When a negative water balance exists, as manifested by an increase in ECF osmolality, thirst and ADH secretion are both stimulated. ADH promotes water reabsorption and hence water conservation.

**Decreased plasma volume** - The thirst centre and ADH secreting cells are both influenced by changes in ECF volume mediated by input from baroreceptors (stretch receptors). The baroreceptors are located in both the low-pressure regions (atria) and the high-pressure regions (carotid sinus and aortic arch) of the circulation (Zerbe & Robertson, 1987), and they monitor venous pressure as a reflection of ECF volume. A volume deficit inhibits the firing of these receptors, which causes a reflex stimulation of both thirst and ADH (thus decreasing urinary output), whereas a volume excess suppresses thirst and ADH secretion. Sagawa et al (1992) studied thirst and drinking in euhydrated and hypohydrated subjects during water immersion. They found a reduction in the sensation of thirst and drinking after immersion in the hypohydrated condition. This reduction occurred without any alterations in plasma sodium, osmolality or arterial pressure, but cardiac output was increased. They concluded that the suppression of drinking upon immersion was due to the loading of the baroreceptors.

Following dehydration, if there is an absence of fluid replacement, plasma volume recovers somewhat at the expense of other body fluid compartments (Stirling & Parsons, 2000). During rehydration, as water is absorbed from the gastrointestinal
tract, there is a preferential restoration and dilution of the plasma volume, decreasing both the volume-dependent and osmotic drives for drinking (Nose et al, 1988b), even though euhydration has not been achieved. A more effective body fluid volume restoration following dehydration is accomplished by providing NaCl with the water during rehydration. This additional NaCl means that plasma sodium remains significantly elevated throughout a greater duration of the rehydration period compared to drinking water alone (Nose et al, 1988b). Thus, the salt dependent thirst drive is maintained and the stimulation of urine production is delayed, leading to a more complete restoration of body water content. Drinking provides a temporary relief of thirst but the negative feedback that follows is caused partially due to the mouth no longer being dry (oropharyngeal dryness), and also due to stomach distension. Nerve endings in the mouth are stimulated by dryness and merely moistening the mouth can often relieve this, even though no water is actually ingested (Laiken & Fanestil, 1990b). Since the body's water needs are only partially met, this suppression is short-lived and the thirst sensation quickly returns.

In a study on thirst following water deprivation in humans (Rolls et al, 1980), sensations associated with thirst were quantitatively measured. Following 24 hours of water deprivation, the sensation of thirst, the dryness of the mouth and the pleasantness of the taste of water diminished very rapidly once drinking began. In fact, large significant changes became evident within 2.5 minutes of the onset of drinking, even though subjects had not achieved euhydration.

Drinking may also take place for a reason other than thirst. Under normal conditions, an individual's desire to drink is driven more by habit and sociological factors (eg. coffee breaks) than by the need to regulate water balance or by thirst (Best & Taylor, 1990). The drive to drink may also be fuelled by factors such as dust, air quality, smoke, or the need to mask an unpleasant taste in the mouth and throat.

In summary, the most powerful signals driving the perception of thirst are those originating from: 1) osmoreceptors as plasma osmolality increases; 2) stretch receptors as blood volume decreases; and 3) dehydration of the mouth and throat. Thirst will be suppressed following dehydration if plain water is consumed, but
maintained if plasma osmolality is increased by consuming fluids containing NaCl. Thirst will also be suppressed immediately upon drinking, but will return once the effects of negative feedback (eg. mouth wetting and stomach distension) have disappeared.

The control of water balance is discussed extensively in Chapter 10.

3.5 Voluntary dehydration

Thirst provides a poor index of body water requirements (Engell et al, 1987), and ad libitum drinking results in incomplete fluid replacement, which has been termed both 'voluntary dehydration' (Bar-Or et al, 1980; Hubbard et al, 1984; Rothstein et al, 1947; Szlyk et al, 1989b) and 'involuntary dehydration' (Greenleaf, 1992; Nose et al, 1988a; Sawka, 1992). It seems the confusion has arisen because in the studies where the term 'voluntary' was used, fluids were freely available, yet hypohydrated subjects did not consume them. Greenleaf (1992) argues that the subject drinks to satiety, but the water debt remains, ie. involuntarily. The debate on terminology continues, but for the purpose of this work, the term 'voluntary dehydration' shall be used, and is defined as the deficit between that fluid consumed and that fluid required by the body, when sufficient beverages are available. The phenomenon has been attributed to the inadequacy of the thirst mechanism to stimulate sufficient drinking for complete rehydration (Greenleaf, 1992; Rothstein et al, 1947), and is most likely to occur when plain water is consumed, as discussed in Section 3.3.

The term 'voluntary dehydration' was first used by Rothstein, Adolph and colleagues in 1947, where they described many of its notable characteristics:

1. When sweating rates are high (>600 g.h⁻¹), drinking only occurs after great losses of body water.
2. If water is impalatable, salty or warm, drinking is restricted.
3. A water deficit accumulated between meals is restored during meals.
4. Drinking is less when subjects are busy or working, and is greater during rest periods. Activity accentuates voluntary dehydration, while leisure reduces it.
5. A distant water supply, or having to boil it, increases voluntary dehydration.

6. During desert hiking, a progressively greater reduction in voluntary dehydration occurs for each succeeding hourly stop for drinking, i.e. 34% replacement after the first hour to 78% replacement after the 6th hour.

7. Increased sodium chloride intake during resting in desert heat did not affect voluntary dehydration.

8. If food is withheld, voluntary water intake is diminished, and vice versa.

9. None of the body water content is superfluous in a man who voluntarily dehydrates. Thus voluntary dehydration is an inhibition of water intake and of the accompanying thirst sensations.

10. Dehydrated men restore less of a water deficit after a second period of dehydration than after the first.

11. The greater the body water deficit, the longer it takes for complete restoration of that deficit.

Since there can be a striking variability between subjects in both sweat loss and fluid intake, Szlyk et al (1989a) suggests that the extent of voluntary dehydration which can occur in hot environments is better described by the ranges of body weight loss and fluid consumption than by average values.

3.6 Why does voluntary dehydration occur?

Anecdotal evidence suggests that in many workplaces where personal protective equipment (PPE) must be worn, wearers avoid consuming fluids in order not to have to doff their PPE to urinate. In some workplaces, such as mines, providing fluid for rehydration has proven problematic due to working conditions (Marshall, 1998). Another cause of voluntary dehydration is a worker being too busy to drink - that is to say that their preoccupation with work / exercise drives them to wait until a rest period before ‘retanking’ (Hubbard et al, 1984). Habitual caffeine drinkers may further contribute to voluntary dehydration (Greenleaf, 1992), since caffeine acts as a diuretic.
It has been shown that liquid temperatures ranging from 10°C to 15°C are preferred by humans when large quantities must be drunk to reduce dehydration (Hubbard et al, 1984; Szlyk et al, 1989b). This highlights the important effects of palatability factors and alliesthesia for fluids in relation to voluntary dehydration (Boulze et al, 1983; Hubbard et al, 1984).

The upper limits for fluid replacement during exercise / heat stress are set by the maximal gastric emptying rates, which approximate 1.0-1.5 l.h⁻¹ for an average adult male (Mitchell & Voss, 1991; Murray, 1987). Gastric emptying rates are reported to decrease during high intensity (>75% VO₂ max) exercise (Costill & Saltin, 1974; Neufer et al, 1989a), hypohydration (Neufer et al, 1989b; Rehre et al, 1990) and heat strain (Neufer et al, 1989b; Owen et al, 1986). Considering sweat rates of 1 l.h⁻¹ are common (Sawka, 1992), and that the highest sweating rate reported so far in the literature was 3.7 l.h⁻¹, which was measured for Alberto Salazar during the 1984 Olympic marathon (Armstrong et al, 1986), it is not surprising that people find it difficult to balance the volume of sweat produced with the volume of fluid consumed. Szlyk et al (1989a) assessed dehydration in young adults during treadmill exercise under dessert conditions when cool water was available ad libitum. They demonstrated a marked variability in fluid intake and dehydration: 40% of the subjects were reluctant to drink, and thus voluntarily dehydrated even when given cool water ad libitum. In a study by Wilk & Bar-Or (1996), the subjective thirst perception was found to be a low sensitivity index of the need to intake fluids, possibly because frequent drinking may have desensitised feelings of mouth dryness and thirst.

Taking into account the findings of various studies, there are a great many factors that could contribute to the development of voluntary dehydration, either singly or in combination. These include perception of thirst (Adolph et al, 1954; Andersson, 1978; Rolls et al, 1980; Sandick et al, 1984), the perception of mouth dryness and taste (Andersson, 1978; Hubbard et al, 1984; Rolls et al, 1980; Sandick et al, 1984), failure to replace electrolytes lost in sweat (Nose et al, 1988b; Takamata et al, 1994), exercise intensity (Maughan et al, 1990), degree of gastric distension (Andersson, 1978; Rolls et al, 1980), tolerance to fluid deprivation (Adolph & Wills, 1947) and the
predisposition to be a heavy or reluctant drinker (Szlyk, 1989a). Other factors may be hot weather experience and background. In addition, volume of fluid through sweating lost does not correlate with fluid intake (Szlyk, 1989a).

3.7 Thirst as a measure of hydration state

It is clear that often thirst will not be a strong enough stimulus to either intake any fluid, or to intake a sufficient amount to satisfy the physiological demands of the body. The reasons for this have been identified as physiological, psychological, sociological and behavioural, and may occur singly or in combination. The fact that thirst has been determined not to occur until a person has lost approximately 1% of body water (Table 1.2) demonstrates that if thirst alone is relied upon, a constant state of hypohydration will be maintained. Therefore, when studying the hydration levels of people working in the heat, the sensation of thirst is not suitable as a sole indicator of the need to intake fluids, and other measures or indicators, which are both practical and accurate (sensitive, valid and reliable), are required. This issue is addressed in Chapters 4 and 5.

3.8 Conclusions

- Thirst is a subjective sensation of the need to drink in order to alleviate a feeling of discomfort in the mouth, but it is driven by a physiological need to replenish diminished body water levels.

- Thirst can be quantified both in terms of the amount of body water lost at its onset, and by the extent of subjective sensations of thirst and dryness of the mouth etc for a given body water deficit.

- Voluntary dehydration occurs when sufficient fluids are available, but are not consumed (in sufficient quantity). If some fluid is consumed it is most likely to happen if the fluid is plain water. Voluntary dehydration can occur due to one or a combination of the following factors: physiological, psychological, sociological and behavioural.
• Thirst is therefore not a reliable indicator of the need to intake fluids, and further indicators or measures are required in addition to thirst. To be good measures of hydration state, they should be sensitive, reliable, valid and practical.
Chapter 4
SENSITIVITY, RELIABILITY AND VALIDITY OF MEASURES OF HUMAN HYDRATION STATE

4.1 Introduction

In order to determine drinking requirements in hot working environments, it is necessary to identify good indicators of hydration state. As discussed in Chapter 3, thirst is not a sufficient stimulus to encourage adequate fluid intake, and therefore more accurate measures or indicators must be sought. To be an accurate measure of human hydration state a technique must be sensitive, reliable and valid. In addition, if the technique is to be applied in work environments, it should also be practical. This chapter examines various measures of hydration state in this respect in order to provide methods of determining water requirements in subsequent studies.

4.1.1 Indicators of hydration state

Many measuring techniques have been used to assess the effects of dehydration on physiological variables during heat and exercise stress. For example, one of the most frequently used is blood sampling by insertion of a catheter into a forearm vein (Costill & Fink, 1974; Costill & Sparks, 1973; Sawka et al, 1992). This allows analyses of variables such as plasma osmolality, plasma electrolytes, plasma protein concentration, plasma lactate, haematocrit, haemoglobin and plasma volume. Plasma volume can also be measured using the radioactive iodine labelled albumin method (Valeri & Altschule, 1981). Total body water can be measured using the ethanol dilution method (Loeppky et al, 1977), which involves consuming ethanol (0.35 / kg of body weight) diluted (four fold) with spring water, and venous blood samples are taken to determine plasma ethanol concentrations.

When measuring the hydration state of people carrying out work in hot environments, it is clear that the above methods of assessing the extent of hypohydration are invasive and impractical, particularly if they are to be used on a regular basis. For this reason, those methods were not used here. This study aimed to investigate alternatives, which
are practical and accurate (reliability, sensitivity, and validity) indicators of hydration state.

The reliability of a measure of hydration state can be defined as the ability of the measure to accurately produce the same results for the same conditions. The sensitivity of a measure of hydration state can be defined as the magnitude of change to take place during the process of dehydration. The validity of a measure of hydration state is how well it represents 'true' hydration state. As we can only gain an indication of this from other measures, the criterion of good correlation with widely recognised indices of hydration state applies, such as urine osmolality and urine specific gravity (Adolph, 1947; Armstrong et al, 1994; Francesconi, 1987 et al; Tipton, 1982). The following variables were measured during a heat and exercise induced dehydration experiment:

4.1.1 Urinary measures

Urine Specific Gravity (U_{sg}) - This is the ratio of the mass of a solution to the mass of an equal volume of water. When the body becomes hypohydrated, the increasing levels of circulating hormones, such as ADH, angiotensin I and aldosterone, mean that urine specific gravity can be used to indicate the extent of the hypohydration. U_{sg} is measured using an hydrometer. Water has a specific gravity of 1.000, and in urine this value increases as dehydration progresses. Normal U_{sg} values range from 1.001-1.035 (Tortora & Anagnostakos, 1990). For body weight losses of >3%, U_{sg} was found to be (mean ± SD) 1.032 ± 0.002 (Francesconi et al, 1987), and a value of (mean ± SD) 1.021 ± 0.008 was found for a mixed sample of males and females, pre- and post-exercise (Armstrong et al, 1994). U_{sg} is one of the most commonly measured indices of urine concentration because of its ease of use, both in the laboratory and field settings.

Urine Osmolality (U_{osm}) - The osmolality of a solution is a measure of the total concentration of discrete solute particles in solution. As with U_{sg}, U_{osm} is used as an indicator of the extent of hypohydration, due to the increasing levels of circulating hormones associated with the process of dehydration and the conservation of vital body fluids this causes. U_{osm} is physiologically more accurate than U_{sg} because it is
unaffected by the volume that the solutes occupy within the solution (Sawka, 1988). The major body fluids follow the iso-osmolality principle, in that they have almost identical osmolalities of approximately 290 mosmol / kg H2O (see Chapter 10 for more detail). This is because the capillary endothelium and almost all cell membranes are freely permeable to water, allowing the plasma, interstitial fluid and intra cellular fluid (ICF) to be iso-osmotic. Urine is one body fluid that differs significantly from 290 mosmol / kg H2O, as it can vary from 70 to 1200 mosmol / kg H2O (Laiken & Fanestil, 1990a). When urine is measured at high levels of ADH or in the absence of ADH, U_{osm} assesses the ability of the kidneys to excrete a maximally concentrated urine (1200 mosmol / kg H2O) or a maximally dilute urine (70 mosmol / kg H2O), respectively. U_{osm} is measured with an osmometer using the freezing point depression method, and a laboratory setting is required. U_{osm} increases as dehydration progresses.

Urine Temperature (U_{temp}) - The temperature of urine inside the body is representative of deep body temperature and can be measured with negligible heat loss after excretion from the body (Parsons, 1993a). As core temperature is affected by many factors, such as exercise, environmental parameters, circadian rhythms and clothing, it is difficult to use it solely as an indicator of hypohydration. However, a critical deficit of 1% of body weight elevates core temperature during exercise, and as the magnitude of water deficit increases, there is a concomitant graded elevation of core temperature during work in the heat (Montain & Coyle, 1992; Sawka et al, 1985). U_{vol} is a non-invasive and straightforward parameter to measure.

Urine Volume (U_{vol}) - Urine volume reflects the body’s current hydration state, so that during sweat induced hypohydration, two things happen: 1) ADH is released in response to increased plasma osmolality, which increases reabsorption of water in the collecting duct; and 2) the accompanying drop in both plasma volume (PV) and blood pressure cause reabsorption of Na^+, and thus water simultaneously. Such water conserving mechanisms produce a more concentrated urine. Although measuring 24-hour urine volume is an accurate method of determining hydration state (Adolph, 1947), it is time consuming and does not provide information at any single time point of the day. Since the production of a concentrated urine is an early indication of the
body's need to conserve fluid during dehydration (Greenleaf, 1992), the measurement of urine volume pre- and post-heat exposure is also useful. The measurement of Ur is also straightforward and practical, and lends itself to application during fieldwork. Normal values for 24-hour urine volume are 1000 - 2000 ml.

Urine Sodium (UNa) - Sodium output from the body is regulated primarily by changes in the amount of Na⁺ excreted in the urine. As previously discussed, the body responds to the need to conserve fluid whilst in a state of hypohydration by releasing hormones that increase reabsorption of sodium in the nephrons, thereby osmotically retaining water. This is reflected by a reduction in the number of sodium ions in the urine. Urinary Na⁺ excretion normally matches input, which for British adults averages 124 mmol/day in (MAFF, 1994), but UNa output can vary from almost negligible amounts (during hypohydration) to over 600 mmol/day (Laiken & Fanestil, 1990a). Sodium in urine can be analysed using flame photometry, which requires a laboratory setting.

Urine Potassium (UK) - Like Na⁺ output, K⁺ output from the body is regulated primarily by changes in the amount of K⁺ excreted in the urine. The hormone aldosterone stimulates secretion of UK. However, aldosterone can affect K⁺ secretion not only in response to changes in K⁺ intake, but also in response to Na⁺ intake. For example, the aldosterone secreted in response to a decrease in Na⁺ intake and plasma volume depletion will stimulate K⁺ secretion. Similarly, when aldosterone is secreted to cause Na⁺ reabsorption, and hence osmotically induced water retention, due to a sweat induced, hypohydration mediated drop in PV, K⁺ will be secreted. Therefore, during states of hypohydration, the number of K⁺ ions in the urine will increase. Urinary K⁺ excretion normally matches input, which for British adults averages 172 mmol/day in (MAFF, 1994), but UK output can vary from less than 10 mmol/day to over 500 mmol/day (Laiken & Fanestil, 1990a). UK is also analysed using flame photometry.

Urine Colour (Ucol) - Armstrong and associates (1994) have developed a urine colour scale as an index of hydration state, due to difficulties in the measuring and interpretation of other urinary indices. They found urine specific gravity and osmolality to be closely related to urine colour. The kidneys produce an amount of
obligatory urine in order to continuously remove dissolved waste products of food breakdown from the body. It is these waste products that give urine its pale straw colour when the body is in water balance; however, since failure to remove these waste products will lead to kidney failure and eventually death, even dehydrated individuals will continue to produce an obligatory amount of urine. Therefore, when body water loss by sweating exceeds water intake, the kidneys act to conserve water, making the urine much more concentrated with waste products and consequently darker in colour. The urine colour chart, which is shown in Appendix II, is extremely practical and does not require expert use. Individuals are advised to attempt to obtain a urine colour equivalent to colours 1, 2 or 3 on the urine colour chart.

**Urine pH (U\(_{\text{PH}}\))** - The pH of a solution = -log [H\(^+\)]. In a healthy individual, the pH of the extra cellular fluid (ECF) generally is maintained within a rather narrow range, with a mean normal value of 7.40 ± 0.02 in arterial plasma and 7.38 ± 0.02 in mixed venous plasma. Such precise control of pH is necessary because of the marked effects of pH changes on protein conformation, enzymatic reactions and central nervous system function. The normal range of U\(_{\text{PH}}\) is 4.6-8.0 (Tortora & Anagnostakos, 1990), the minimum U\(_{\text{PH}}\) is 4.5 (Laiken & Fanestil, 1990a), and values decrease with dehydration. U\(_{\text{PH}}\) can be measured using litmus paper.

### 4.1.3 Haematological Measures

**Haematocrit (Hct)** - this is the percentage of blood made up by red blood cells, calculated by centrifuging a blood sample and ‘reading off’ the volume occupied by the red blood cells. Plasma provides the precursor fluid for sweat. Therefore, when a person is hypohydrated, a blood sample will contain less plasma, and thus a greater percentage of red blood cells (RBC) than when they are euhydrated. This is known as polycythemia, due to dehydration (Myhre & Robinson, 1977; Van Beaumont *et al*, 1974). Normal values for Hct are 40-54% for males and 37-47% for females (Tortora & Anagnostakos, 1990; Van de Graaff & Fox, 1992). Blood pinprick samples are sufficient to measure Hct and Hb, but a sterile immediate environment is absolutely necessary.
Haemoglobin (Hb) - Haemoglobin constitutes about 33% of the cell volume. The increase in plasma osmolality that results from dehydration is associated with a decrease in mean corpuscular volume (MCV), which is reflected by a greater proportion of the cell being occupied by Hb. Costill and Fink (1974) found that for both thermally and exercise induced dehydration, on average, a 4% hypohydration level resulted in a 5.6% increase in plasma osmolality and a 4.5% reduction in MCV. Normal Hb values are 13.5-18 g/100ml for males and 12-16 g/100ml for females (Tortora & Anagnostakos, 1990; Van de Graaff & Fox, 1992).

Change in Plasma Volume (ΔPV) - Previously, percentage change in plasma volume was calculated using a method involving venous haematocrit (Van Beaumont, 1972). The method assumes that RBC size remains constant. However, since it is known that plasma osmolality increases with dehydration, it was hypothesised and found that red cell size can decrease (Costill & Fink, 1974; Dill & Costill, 1974). The volume of plasma in 100 ml blood at rest (PV_{B}) is equal to 100 minus the haematocrit (%). Due to changes in MCV during heat exposure, another method (Dill & Costill, 1974) was used in this study to calculate plasma volume after the exposure. Changes in blood volume (BV) and red cell volume (CV) must first be calculated. The subscripts B and A refer to before and after dehydration, and BV_{B} was taken as 100.

\[
\begin{align*}
BV_{A} &= BV_{B} \frac{Hb_{B}}{Hb_{A}} \quad \text{(Eq. 4.1)} \\
CV_{B} &= BV_{B} \frac{Hct_{B}}{Hct_{A}} \quad \text{(Eq. 4.2)} \\
CV_{A} &= BV_{A} \frac{Hct_{A}}{Hct_{A}} \quad \text{(Eq. 4.3)} \\
PV_{B} &= BV_{B} - CV_{B} \quad \text{(Eq. 4.4)} \\
PV_{A} &= BV_{A} - CV_{A} \quad \text{(Eq. 4.5)} \\
\%ΔPV &= 100 \frac{PV_{A} - PV_{B}}{PV_{B}} \quad \text{(Eq. 4.6)}
\end{align*}
\]

Maintenance of PV and blood pressure are essential for the cardiovascular system to function properly. Sweat induced hypohydration will decrease PV (Nadel et al, 1980; Sawka et al, 1985) and increase plasma osmolality in proportion to the level of fluid loss (Sawka, 1996), which is why they are measured in heat / exercise stress studies. Plasma volume decreases because it provides the precursor fluid for sweat, and osmolality increases because sweat is ordinarily hypotonic relative to plasma. It is the
plasma hyperosmolality that causes fluid to move from the intra-to the extra-cellular compartments to enable plasma volume defence in hypohydrated subjects. However, because of this shift in body fluids, changes in hydration state are not always accurately reflected in haematological indices. Francesconi et al (1987) hypothesised that plasma variables are unaffected until a threshold level of body weight loss (>3% of body weight) has been achieved.
4.1.4 Sweat Measures

Sweat rate (Sw R) and percentage of body weight loss (% BW loss) - These measures can be easily calculated using accurate weighing scales to measure sweat loss, incorporating the time spent working where appropriate.

Sweat sodium (SwNa) and sweat potassium (SwK) - In acclimatised subjects, the amount of electrolytes lost in sweat are modified (see Chapter 2), so that as sweat rate increases, sweat sodium, for example, decreases (Sawka, 1992). Therefore, less solute is lost from the plasma for a given sweat rate for an acclimated subject when compared to an unacclimatised subject. It follows that the greater amount of solute left in the plasma, the more fluid will move from the intracellular to the extracellular space due to the concentration gradient, thereby defending the blood plasma volume. As the amount of electrolytes lost in sweat for unacclimatised individuals is unmodified, sweat sodium, for example, will increase with sweat rate, making it difficult to maintain plasma volume. This is detrimental for a subject already in a state of hypohydration. Collection of sweat for analysis of electrolytes is not especially convenient, but was nevertheless carried out in this study using a patch collecting method. This method would be particularly inconvenient whilst monitoring in an industrial setting, for example.

4.1.5 Aim of the study

The aim of this study was to investigate each of the measures in terms of sensitivity, reliability, validity and also practicality, in order that the results can be used to provide a method for assessing water requirements in hot working environments.

4.2 Method

The study was approved by Loughborough University Ethical Advisory Committee (G98/P2). Subjects gave voluntary and written informed consent, and adhered to the regulations set out in the Loughborough University Human Thermal Environments Laboratory's 'Application to Take Part in Thermal Experiments' (Appendix I).
4.2.1 Preliminary testing
All subjects completed an incremental cycle ergometer test for the determination of VO₂ max by prediction (ACSM, 1991). Measures of height, weight and skinfold thickness were taken using the equipment and techniques described in Section 2.2.1. This preliminary session was also used to familiarise the subjects with the experimental setting and procedure.

4.2.2 Subjects
Eight male subjects, who were unacclimatised to heat, participated in this study. The subjects had a mean (± SD) age of 24 ± 4 yr, height of 1.81 ± 0.09 m, weight of 80.1 ± 7.9 kg, percent body fat of 16.8 ± 4.3 %, and predicted maximal 0₂ uptake of 4.58 ± 0.87 l/min.

4.2.3 Experimental design
Subjects participated in the protocol on two occasions, (with at least one week between sessions), exercising on a cycle ergometer (Monarch) in a hot, dry environment (mean ± SD: 40.3 ± 0.1 °C air temperature, 34.3 ± 0.3 % relative humidity, 0.4 ± 0.2 m s⁻¹ air velocity). This environment was chosen to potentiate rapid evaporative heat loss from the body to the environment, and to reduce the effects of sweat dripping from the skin and the effects of hidromeiosis on sweat production. Each heat exposure lasted 170 minutes in duration, consisting of five sets of 20 minutes cycling and 10 minutes rest. On one occasion, subjects were given cool water (T_wat 5.4 ± 0.5°C) (cold fluids of ~5°C are emptied from the stomach at a faster rate than fluids at body temperature (Costill & Saltin, 1974)) to drink, which was measured to match the rate at which sweat was lost (drinking condition). Subjects were weighed after each of the five cycle sessions, and they were given the equivalent of the body mass lost to drink during the next cycle session. On the other occasion, subjects received no fluid replacement (no drink condition).

A battery of physiological tests were carried out pre- and post-exposure. Subjects’ work rate on the cycle ergometers was kept at 234 W/m² for the first two cycles, 198 W/m² for the third and fourth cycles, and 162 W/m² for the last cycle. The sweat rate required in order to prevent an excessive increase in temperature was calculated for
this exercise regime according to an International Standard (ISO 7933, 1989). The standard predicted that a sweat rate of 534 g/hr would be required or 1513 grams for 170 minutes. All tests began at ~0930 h to control for diurnal patterns.

4.2.4 Dietary control

To ensure that subjects were in similar hydration and nutritional states at the start of each experimental session, diet, fluid intake and exercise during the 15 hours preceding each trial were controlled. Subjects ate the same menu of food as each other, and ate the same menu on each occasion. They were not permitted to eat anything extra, and had to consume all food and drink provided. Subjects were not permitted any alcohol, caffeine, or added salt or sugar, and drank only water. They were encouraged to drink plenty of water, but in addition, subjects were instructed to drink ≥ 500 ml of water each prior to going to sleep (approximately 9 hours before testing) and after waking on the day of testing, to decrease the likelihood that they would begin the testing in a hypohydrated state (Nose et al, 1988a). Subjects were not permitted to exercise from 6pm the night before the experiment.

4.2.5 Procedure

Subjects were clad only in padded cycling shorts, which were weighed pre- and post-exposure to calculate the sweat held in them. Subjects were instrumented in a thermally neutral preparation room. Mean aural temperature (T₁), four point mean skin temperature (Tₖ) and heart rate (HR) were recorded continuously from this point until the experiment was completed (using the equipment and techniques described in Section 2.2.1). Sweat collection patches were attached at seven sites over the body, as described in Section 2.2.4 (the lower back site was not used in this study). Sweat was absorbed on 40mm squares of filter paper (Whatman 4 Qualitative 110 mm). The filter paper was held in place by patches made of polythene and Transpore™ (3M 25 mm) tape. It was considered that the patches did not encourage less sweating on these sites than on the rest of the body, as Transpore™ tape is permeable to liquid, and the patches were ventilated with the regular replacement of the filter paper squares.

Subjects entered the environmental chamber and sat quietly for 15 minutes, during which time a battery of physiological measures were taken. Subjects produced a pre-
exposure urine sample, were weighed, and gave sublingual temperature ($T_{m}$) and blood pinprick samples. Subjects in the drinking condition were given a volume of water to drink equal to the volume of their urine sample. Subjects then mounted the cycle ergometers and began the pattern of cycling for 20 minutes, and resting for 10 minutes. Between cycle bouts, measures of weight loss and sublingual temperature only were taken, and all seven filter paper squares were replaced in the sweat patches. Urine samples and blood pinprick samples were taken pre- and post-exposure. Subjective scales of overall thermal sensation (ASHRAE sensation scale, 1966) (Figure 2.2) and thirst (Figure 4.1) were completed pre-exposure, and after every bout of cycling. Some of the procedures carried out are shown in Plate 4.1.

3 Very thirsty  
2 Thirsty  
1 Slightly thirsty  
0 Not thirsty

Figure 4.1: Thirstiness scale

Plate 4.1: Some of the procedures carried out during the experiment: cycling, drinking, weighing

4.2.6 Measurements

Subjects were weighed after each cycle bout, as well as pre- and post-exposure, in order that weight loss over time could be observed in addition to the total. Filter papers were placed in the sweat patches immediately before the subject mounted the cycle ergometer each time, and removed upon dismounting. This continuous replacement allowed for comparison of sweat samples throughout the exposures and also between conditions. Filter papers were immediately transferred from the skin to
sealable plastic bags to prevent evaporation. The sweat samples were analysed for sodium (SwNa) and potassium (SwK) concentration using flame photometry (as described in Section 2.2.10). Blood pinprick measures were used to determine the change in haemoglobin (Hb), haematocrit (Hct) and plasma volume (PV) over the exercise period and between conditions. Haematocrit was measured by introducing the samples into microcapillary tubes and centrifuging, using the microhaematocrit technique (Hawksley Micro-haematocrit Centrifuge & Reader, Hawksley & Sons, England). Haematocrit values were corrected (0.96) for plasma trapped within the packed red cells (Costill & Fink, 1974). Haemoglobin was measured by introducing the samples to a cyanmethemoglobin reagent solution, and analysed using the colorimetric method (Boehringer Mannheim GmbH Diagnostica) (Van Kampen & Zijlstra, 1961; ICSH, 1967). Hct and Hb measures were taken in triplicate. Change in plasma volume was calculated according to the method described in Dill & Costill (1974). Urine samples were provided pre-, post- and 6 hours post-exposure. The following measures were taken from the urine samples: temperature (U_temp); volume (U_vol); pH (U_ph); colour (U_col); specific gravity (U_sg); urine sodium (U_Na); urine potassium (U_K); and urine osmolality (U_osm). Urine temperature was obtained when a subject urinated into a vacuum flask kept at 37°C. (This was not possible for the 6 hour post-exposure samples). Urine samples were then transferred to measuring cylinders for volume measurements, which was again not possible for the 6 hour post-exposure samples. Urine pH was determined using litmus paper (Whatman Full Range pH 1-14), and was always judged by the same experimenter. The colour of the urine was judged using a ‘urine colour chart’ developed during field and laboratory studies at the University of Connecticut Human Performance Laboratory (Armstrong, 1994). Each sample was held up to the colour chart in natural daylight; the same experimenter always carried out this procedure. The eight-colour scale included colours ranging from very pale yellow to brownish-green. In order to standardise the colours in the scale, Armstrong compared them to a classic compendium of colours published by Maerz & Paul (1950) and matched the following standardised samples (plate / grid number): Colour 1, 17/B1; Colour 2, 9/H1; Colour 3, 17/J1; Colour 4, 17/L1; Colour 5, 9/I3; Colour 6, 9/L3; Colour 7, 12/K6; Colour 8, 23/L1.). The sodium and potassium content of urine were determined by flame photometry. Urine specific gravity was measured using a glass hydrometer (Boots Company PLC, Nottingham, England). Urine osmolality was analysed with an osmometer and
associated equipment (Fison’s Whirlimixer, Eppendorf Centrifuge 5415C, Gonotec GMBH measuring vessels, Gonotec Calibration Solution 300 mOsmol/kg NaCl in H₂O, and a Gonotec Osmomat 030-Automatic Cryoscopic Osmometer). Plate 4.2 demonstrates some of the sampling techniques used in the study.

Plate 4.2: Sampling techniques: sweat collection patches, blood sampling and oral temperature

4.2.7 Calibration

Analysis of all samples was carried out in triplicate. For flame photometry, standard solutions were used to calibrate the equipment and to compare the samples with. During sweat analysis, plain, dry filter paper was also analysed to ensure any sodium or potassium present before sweat absorption could be accounted for. The osmometer was calibrated with calibration solution throughout the analyses. The colorimeter used to measure haemoglobin was calibrated between each set of measurements, and distilled water was also run through the meter as a further check. The Pyrex measuring cylinders used had the following tolerance levels:

<table>
<thead>
<tr>
<th>Volume (ml)</th>
<th>Gradations (ml)</th>
<th>Tolerance (± ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.0</td>
<td>0.6</td>
</tr>
<tr>
<td>250</td>
<td>2.0</td>
<td>1.4</td>
</tr>
</tbody>
</table>

As a further check, the cylinders were weighed, and then again whilst containing 100 ml of water according to each cylinder, as the density of water is known. Skin and aural thermistors were calibrated to within ± 0.2°C, using a water calibration tank and excluding thermistors which fell outside of this range.
4.2.8 Statistical analyses

Reliability coefficients were calculated for the pre-exposure measures for each variable. The Student’s t-test was used in order to determine the sensitivity of urine, haematological and sweat variables. Pearson product moment correlation coefficients were calculated to determine the validity of each of the measures (Spearman’s rank correlation was used where appropriate). The Wilcoxon signed-ranks test was used to analyse measures of thermal sensation, thirst and thermal comfort. Significance was determined at the $p < .05$ confidence level (where the Bonferroni correction was applied, the significance will be denoted thus: $p^b < .05$), and all terms were expressed as the mean $\pm SD$. 
4.3 Results

The variables measured during the experiment are presented in Tables 4.2, 4.3 and 4.4. All measurements in Table 4.2 are urine variables, taken pre-exposure, post-exposure and 6 hours post-exposure, except urine temperature and volume, which were not measured 6 hours post-exposure. Table 4.3 presents haematological measurements taken pre- and post-exposure, and also sweat variables taken at intervals throughout exercise. Table 4.4 shows physiological measures of thermal state taken throughout the experiment.

4.3.1 Reliability of measures

If an indicator of hydration state is reliable, it should reproduce the same results under the same conditions. Therefore, reliability coefficients were calculated for the pre-exposure values for both conditions, since preparation was the same for each condition. The reliability coefficients were calculated according to the method of Winer (1971), and are shown in Table 4.1. R-squared provides an estimate of the proportion of shared variance between the two measures and can be interpreted accordingly. Reliability should be above 0.7. Traditionally, r above 0.8 (r-squared > 0.6) is considered to be good, and r above 0.9 (r-squared > 0.8) is considered to be excellent (Nunally, 1978; Streiner & Norman, 1989).

Table 4.1: Reliability coefficients for pre-exposure variables

<table>
<thead>
<tr>
<th>Measure</th>
<th>Reliability coefficient (r)</th>
<th>R-squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>U_osm</td>
<td>0.946**</td>
<td>0.895</td>
</tr>
<tr>
<td>U_ag</td>
<td>0.948**</td>
<td>0.899</td>
</tr>
<tr>
<td>U_temp</td>
<td>0.447</td>
<td>0.200</td>
</tr>
<tr>
<td>U_vol</td>
<td>0.869*</td>
<td>0.755</td>
</tr>
<tr>
<td>U_col</td>
<td>0.901**</td>
<td>0.812</td>
</tr>
<tr>
<td>U_ph</td>
<td>-0.213</td>
<td>0.045</td>
</tr>
<tr>
<td>U_H</td>
<td>0.539</td>
<td>0.291</td>
</tr>
<tr>
<td>U_K</td>
<td>0.665</td>
<td>0.442</td>
</tr>
<tr>
<td>Hct</td>
<td>0.627</td>
<td>0.393</td>
</tr>
<tr>
<td>Hb</td>
<td>0.690</td>
<td>0.476</td>
</tr>
<tr>
<td>SwNa</td>
<td>0.914**</td>
<td>0.835</td>
</tr>
<tr>
<td>SwK</td>
<td>0.162</td>
<td>0.026</td>
</tr>
</tbody>
</table>

* r > 0.8  ** r > 0.9
<table>
<thead>
<tr>
<th>Measurement</th>
<th>Time</th>
<th>M ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No drinking</td>
<td>Drinking</td>
</tr>
<tr>
<td>Urine Colour</td>
<td>Pre</td>
<td>2 ± 1*</td>
<td>1-4</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>6 ± 1**</td>
<td>3 ± 2</td>
</tr>
<tr>
<td></td>
<td>6 hours post</td>
<td>4 ± 2</td>
<td>4 ± 2</td>
</tr>
<tr>
<td>Urine Specific Gravity</td>
<td>Pre</td>
<td>1.009 ± 0.008*</td>
<td>1.001 - 1.020</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>1.023 ± 0.005**</td>
<td>1.016 - 1.028</td>
</tr>
<tr>
<td></td>
<td>6 hours post</td>
<td>1.014 ± 0.010</td>
<td>1.002 - 1.027</td>
</tr>
<tr>
<td>Urine Temperature</td>
<td>Pre</td>
<td>36.7 ± 0.25*</td>
<td>36.4 - 37.2</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>37.6 ± 0.4</td>
<td>37.3 - 38.2</td>
</tr>
<tr>
<td></td>
<td>6 hours post</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Urine pH</td>
<td>Pre</td>
<td>5.5 ± 1.5</td>
<td>3 - 7.5</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>5 ± 1</td>
<td>3 - 6</td>
</tr>
<tr>
<td></td>
<td>6 hours post</td>
<td>6 ± 1.5</td>
<td>3 - 7</td>
</tr>
<tr>
<td>Urine Volume</td>
<td>Pre</td>
<td>253 ± 197*</td>
<td>106 - 574</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>304 ± 214</td>
<td>106 - 928</td>
</tr>
<tr>
<td></td>
<td>6 hours post</td>
<td>104 ± 71**</td>
<td>35 - 229</td>
</tr>
<tr>
<td>Urine Sodium</td>
<td>Pre</td>
<td>72.8 ± 50.5</td>
<td>19.6 - 156.5</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>63 ± 36.6</td>
<td>18.5 - 134.8</td>
</tr>
<tr>
<td></td>
<td>6 hours post</td>
<td>71.5 ± 37.9</td>
<td>28 - 126.1</td>
</tr>
<tr>
<td>Urine Potassium</td>
<td>Pre</td>
<td>34.3 ± 24.6*</td>
<td>5.1 - 72.9</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>86.8 ± 39.8</td>
<td>56.1 - 42.6</td>
</tr>
<tr>
<td></td>
<td>6 hours post</td>
<td>58.5 ± 45.6</td>
<td>56.4 - 37.6</td>
</tr>
<tr>
<td>Urine Osmolality</td>
<td>Pre</td>
<td>286 ± 150*</td>
<td>160 - 480</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>688 ± 153**</td>
<td>422-859</td>
</tr>
<tr>
<td></td>
<td>6 hours post</td>
<td>545 ± 259</td>
<td>301-989</td>
</tr>
</tbody>
</table>

* p < .05 pre- vs post-exposure (no drinking)  ** p < .05 post no drinking vs post drinking
Table 4.3: Haematological measurements taken pre- and post-exposure, and sweat measurements taken at intervals throughout exercise for no drinking and drinking conditions (M, SD, range)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Time</th>
<th>M ± SD No drinking</th>
<th>M ± SD Drinking</th>
<th>M ± SD No drinking</th>
<th>M ± SD Drinking</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No drinking</td>
<td>Drinking</td>
<td>No drinking</td>
<td>Drinking</td>
</tr>
<tr>
<td>Haematocrit</td>
<td>Pre</td>
<td>45 ± 4</td>
<td>44 ± 2</td>
<td>39.5 - 50</td>
<td>42 - 46.5</td>
</tr>
<tr>
<td>(Hct, %) Ψ</td>
<td>Post</td>
<td>44.5 ± 2</td>
<td>43.5 ± 2.5</td>
<td>42 - 48</td>
<td>39 - 47.5</td>
</tr>
<tr>
<td></td>
<td>6 hours post</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Haemoglobin</td>
<td>Pre</td>
<td>15.74 ± 2.23*</td>
<td>16.11 ± 1.69</td>
<td>13.24 - 20.59</td>
<td>13.6 - 18.2</td>
</tr>
<tr>
<td>(Hb, g/100ml)</td>
<td>Post</td>
<td>16.71 ± 2.8</td>
<td>16.02 ± 1.58</td>
<td>14.71 - 22.8</td>
<td>14.16 - 19.12</td>
</tr>
<tr>
<td></td>
<td>6 hours post</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Sweat Sodium</td>
<td>Patch change 1</td>
<td>2.67 ± 1.15*</td>
<td>2.74 ± 1.01</td>
<td>0.88-4.63</td>
<td>1.13-3.88</td>
</tr>
<tr>
<td>(SwNa, mg)</td>
<td>Patch change 2</td>
<td>3.86 ± 1.43</td>
<td>3.77 ± 1.34</td>
<td>1.5-6.5</td>
<td>1.63-5.38</td>
</tr>
<tr>
<td></td>
<td>Patch change 3</td>
<td>4.56 ± 2.09</td>
<td>4.6 ± 1.78</td>
<td>1.5-7.75</td>
<td>1.75-7.25</td>
</tr>
<tr>
<td></td>
<td>Patch change 4</td>
<td>4.89 ± 1.87</td>
<td>4.51 ± 1.78</td>
<td>1.88-7.63</td>
<td>1.63-6.25</td>
</tr>
<tr>
<td></td>
<td>Patch change 5</td>
<td>4.88 ± 1.97</td>
<td>4.42 ± 1.51</td>
<td>2.5-8.5</td>
<td>2.13-5.75</td>
</tr>
<tr>
<td>Sweat Potassium</td>
<td>Patch change 1</td>
<td>550 ± 134</td>
<td>498 ± 188</td>
<td>350-760</td>
<td>90-700</td>
</tr>
<tr>
<td>(SwK, μg)</td>
<td>Patch change 2</td>
<td>614 ± 81</td>
<td>526 ± 170</td>
<td>500-750</td>
<td>130-650</td>
</tr>
<tr>
<td></td>
<td>Patch change 3</td>
<td>584 ± 234</td>
<td>578 ± 209</td>
<td>390-1050</td>
<td>140-860</td>
</tr>
<tr>
<td></td>
<td>Patch change 4</td>
<td>694 ± 171</td>
<td>538 ± 206</td>
<td>500-940</td>
<td>130-840</td>
</tr>
<tr>
<td></td>
<td>Patch change 5</td>
<td>578 ± 204</td>
<td>546 ± 221</td>
<td>320-900</td>
<td>170-930</td>
</tr>
</tbody>
</table>

* p^b < .05 pre- vs post-exposure (no drinking)  Ψ Hct = observed Hct x 0.96
Table 4.4: Measures of thermal state for no drinking and drinking conditions (M, SD, range)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Time</th>
<th>No drinking</th>
<th>Drinking</th>
<th>No drinking</th>
<th>Drinking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart Rate (HR, bpm)</td>
<td>Pre</td>
<td>75 ± 14</td>
<td>78 ± 13</td>
<td>53 - 100</td>
<td>64 - 100</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>159 ± 23*</td>
<td>149 ± 26*</td>
<td>130 - 189</td>
<td>120 - 187</td>
</tr>
<tr>
<td>Aural Temperature</td>
<td>Pre</td>
<td>36.3 ± 0.3</td>
<td>36.3 ± 0.3</td>
<td>35.8 - 36.7</td>
<td>35.7 - 36.7</td>
</tr>
<tr>
<td>(T_{aur}, °C)</td>
<td>Post</td>
<td>37.7 ± 0.3*</td>
<td>37.2 ± 0.5*</td>
<td>37.2 - 38.1</td>
<td>36.5 - 37.9</td>
</tr>
<tr>
<td>Skin Temperature</td>
<td>Pre</td>
<td>31.2 ± 0.9</td>
<td>31.2 ± 1.6</td>
<td>29.8 - 32.8</td>
<td>29.7 - 34.4</td>
</tr>
<tr>
<td>(T_{sk}, °C)</td>
<td>Post</td>
<td>36.8 ± 0.4*</td>
<td>36.4 ± 0.7*</td>
<td>36.1 - 37.3</td>
<td>35.2 - 37.4</td>
</tr>
<tr>
<td>Oral Temperature</td>
<td>Pre</td>
<td>36.5 ± 0.2</td>
<td>36.6 ± 0.3</td>
<td>36.2 - 36.9</td>
<td>36.3 - 37.2</td>
</tr>
<tr>
<td>(T_{or}, °C)</td>
<td>Post</td>
<td>37.4 ± 0.3*</td>
<td>37.0 ± 0.5</td>
<td>36.8 - 37.9</td>
<td>36.4 - 37.7</td>
</tr>
<tr>
<td>Sweat Rate (SwR, l/hr^-1)</td>
<td>Post cycle 1</td>
<td>1.087 ± 0.302</td>
<td>0.637 ± 0.101</td>
<td>0.864 - 1.702</td>
<td>0.514 - 0.83</td>
</tr>
<tr>
<td>Total sweat loss (litres)</td>
<td>Overall</td>
<td>2.324 ± 0.189</td>
<td>2.072 ± 0.134/</td>
<td>1.988 - 2.564</td>
<td>1.863 - 2.248</td>
</tr>
<tr>
<td>Body weight loss (%)</td>
<td>Overall</td>
<td>2.85 ± 0.29</td>
<td>2.56 ± 0.24</td>
<td>2.45 - 3.27</td>
<td>2.27 - 3.02</td>
</tr>
</tbody>
</table>

*p < .05  * pre vs post  \( \Psi \) no drink vs drinking  (for sweat measurements, only total sweat loss was compared statistically)
4.3.2 Sensitivity of measures

In order to ascertain whether the measures were sensitive to the process of dehydration, the pre- and post-exposure values for the no drinking condition were compared. Significant results are shown in Tables 4.2 and 4.3. The values that changed significantly during dehydration, and therefore were sensitive, were ($p^b > .05$):

$$U_{col} \quad U_{sg} \quad U_{vol} \quad U_{temp} \quad U_K \quad U_{osm} \quad Sw_{Na} \quad Hb$$

It is likely that the subjects in the drinking condition were not completely euhydrated at the end of the exposure, as the fluid consumed following the last exercise would not have been absorbed in the gut. Therefore, it was necessary to compare post-exposure measures for both conditions to determine which of the measures was more sensitive in determining the difference between the conditions (of varying levels of hypohydration). (There were no significant differences in measures between the conditions for pre-exposure values). The values that were significantly different ($p^b > .05$) between the conditions after the exposure are shown in Table 4.2 and were:

$$U_{vol} \quad U_{col} \quad U_{sg} \quad U_{osm}$$

Therefore, the preceding four measures of hydration state were shown to be the most sensitive to the process of dehydration.

4.3.3 Validity of measures

The validity of the measures was determined by correlating them with widely recognised measures of hydration state, $U_{osm}$ and $U_{sg}$, for pre-, post- and 6 hours post-exposure values. The correlation coefficients are shown in Table 4.5 for the no-drinking condition, and in Table 4.6 for the drinking condition. As expected, the recognised measures of hydration state, $U_{osm}$ and $U_{sg}$, correlated significantly ($p^b < .05$) with one another at all times and for both conditions. In addition, $U_{col}$ correlated significantly with them at all times and for both conditions ($p^b < .05$). Although $U_{vol}$, $U_{Na}$ and $U_K$ correlated well with $U_{osm}$ and $U_{sg}$ in the drinking condition ($p^b < .05$ for pre- and post-exposure), they did not in the no drink condition.
The relationships between $U_{sg}$, $U_{col}$ and $U_{osm}$ for pre-, post- and 6 hours post-exposure are shown in Figures 4.2 – 4.19, as they demonstrated the highest and most consistent significant correlations of all the urinary, haematological and sweat measures. The correlation coefficients are shown on each graph, and all relationships were significant ($p^b < .05$).

4.3.4 The most reliable, sensitive and valid measures

To summarise the results of the tests carried out in Sections 4.3.1, 4.3.2 and 4.3.3, the following measures were shown to be the most reliable, sensitive and valid indicators of hydration state:

$U_{col}$ $U_{sg}$ $U_{osm}$

4.3.5 Post experimental drinking

The subjects' drinking regimes were not controlled once they left the laboratory setting; however, subjects filled in questionnaires detailing their fluid consumption in the 6 hours following exercise. Analysis showed that when subjects completed the no drinking condition, they consumed significantly more fluids ($p^b < .05$) than when they completed the drinking condition.

4.3.6 Subjective measures

Subjective measures of thermal sensation, comfort and thirst were taken at the beginning of the exposure, and then after every cycle bout during both conditions. The subjective measures were compared between conditions after cycles 1, 3 and 5 (to reduce the number of comparisons). There were no significant differences in feelings of thermal comfort or thermal sensation between the conditions. Subjects felt significantly more thirsty in the no drink condition than the drinking condition on completion of cycle 5 ($p^b < .05$).
### Table 4.5: No drinking condition: correlation coefficients for each measure against $U_{osm}$ and $U_{sg}$

<table>
<thead>
<tr>
<th>Measure</th>
<th>Pre-exposure</th>
<th>Post-exposure</th>
<th>6 hours post-exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$U_{osm}$</td>
<td>$U_{sg}$</td>
<td>$U_{osm}$</td>
</tr>
<tr>
<td>$U_{osm}$</td>
<td>-</td>
<td>+0.981*</td>
<td>-</td>
</tr>
<tr>
<td>$U_{sg}$</td>
<td>+0.981*</td>
<td>-</td>
<td>+0.984*</td>
</tr>
<tr>
<td>$U_{temp}$</td>
<td>-0.585</td>
<td>-0.573</td>
<td>+0.745</td>
</tr>
<tr>
<td>$U_{col}$</td>
<td>-0.567</td>
<td>-0.653</td>
<td>-0.676</td>
</tr>
<tr>
<td>$U_{col}\Psi$</td>
<td>+0.964*</td>
<td>+0.802*</td>
<td>+0.932*</td>
</tr>
<tr>
<td>$U_{pH}$</td>
<td>-0.024</td>
<td>-0.064</td>
<td>-0.324</td>
</tr>
<tr>
<td>$U_{Na}$</td>
<td>+0.232</td>
<td>+0.370</td>
<td>+0.582</td>
</tr>
<tr>
<td>$U_{K}$</td>
<td>+0.392</td>
<td>+0.497</td>
<td>+0.525</td>
</tr>
<tr>
<td>$Ht$</td>
<td>-0.577</td>
<td>-0.585</td>
<td>-0.135</td>
</tr>
<tr>
<td>$Hb$</td>
<td>-0.384</td>
<td>-0.358</td>
<td>-0.533</td>
</tr>
<tr>
<td>$SW_{Na}$</td>
<td>-0.417</td>
<td>-0.358</td>
<td>+0.524</td>
</tr>
<tr>
<td>$SW_{K}$</td>
<td>-0.276</td>
<td>-0.254</td>
<td>-0.633</td>
</tr>
</tbody>
</table>

* $p < .05$  
Ψ Spearman's Rank analysis

### Table 4.6: Drinking condition: correlation coefficients for each measure against $U_{osm}$ and $U_{sg}$

<table>
<thead>
<tr>
<th>Measure</th>
<th>Pre-exposure</th>
<th>Post-exposure</th>
<th>6 hours post-exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$U_{osm}$</td>
<td>$U_{sg}$</td>
<td>$U_{osm}$</td>
</tr>
<tr>
<td>$U_{osm}$</td>
<td>-</td>
<td>+0.974*</td>
<td>-</td>
</tr>
<tr>
<td>$U_{sg}$</td>
<td>+0.974*</td>
<td>-</td>
<td>+0.985*</td>
</tr>
<tr>
<td>$U_{temp}$</td>
<td>-0.554</td>
<td>-0.641</td>
<td>-0.547</td>
</tr>
<tr>
<td>$U_{col}$</td>
<td>-0.778*</td>
<td>-0.786*</td>
<td>-0.774*</td>
</tr>
<tr>
<td>$U_{col}\Psi$</td>
<td>+0.926*</td>
<td>+0.931*</td>
<td>+0.933*</td>
</tr>
<tr>
<td>$U_{pH}$</td>
<td>+0.763</td>
<td>+0.729</td>
<td>+0.346</td>
</tr>
<tr>
<td>$U_{Na}$</td>
<td>+0.903*</td>
<td>+0.791*</td>
<td>+0.773*</td>
</tr>
<tr>
<td>$U_{K}$</td>
<td>+0.904*</td>
<td>+0.810*</td>
<td>+0.801*</td>
</tr>
<tr>
<td>$Ht$</td>
<td>+0.112</td>
<td>+0.037</td>
<td>+0.255</td>
</tr>
<tr>
<td>$Hb$</td>
<td>-0.083</td>
<td>-0.122</td>
<td>+0.531</td>
</tr>
<tr>
<td>$SW_{Na}$</td>
<td>-0.271</td>
<td>-0.325</td>
<td>-0.339</td>
</tr>
<tr>
<td>$SW_{K}$</td>
<td>+0.439</td>
<td>+0.486</td>
<td>+0.321</td>
</tr>
</tbody>
</table>

* $p < .05$  
Ψ Spearman's Rank analysis
Figure 4.2: No drink, pre-exposure

Figure 4.3: No drink, pre-exposure

Figure 4.4: No drink, pre-exposure

Figure 4.5: No drink, post-exposure

Figure 4.6: No drink, post-exposure

Figure 4.7: No drink, post-exposure

Figure 4.8: No drink, 6 hrs post-exposure

Figure 4.9: No drink, 6 hrs post-exposure
Figure 4.10: No drink, 6 hrs post-exposure

Figure 4.11: Drinking, pre-exposure

Figure 4.12: Drinking, pre-exposure

Figure 4.13: Drinking, pre-exposure

Figure 4.14: Drinking, post-exposure

Figure 4.15: Drinking, post-exposure

Figure 4.16: Drinking, post-exposure

Figure 4.17: Drinking, 6 hrs post-
4.4 Discussion

The aim of this study was to assess several physiological indicators of hydration state in terms of reliability, sensitivity, validity and also practicality, in order that the results could be used to provide a method for determining water requirements in hot working environments.

It is possible that the two conditions for this experiment may have been termed 'hypohydration' (for the no drink condition) and 'euhydration' (for the drinking condition). However, the term euhydration would be questionable, as although the subjects were given an equal volume of fluid to drink as that lost as sweat, the process of gastric emptying, which can take 10-60 minutes for water (Rehrer et al, 1989), means that the fluid is not immediately available for the body to use. Therefore, the term 'drinking condition' was used instead.

4.4.1 Measures of thermal state during heat exposure

There were significant increases ($p^b < .05$) over the heat exposure in each of heart rate, aural temperature, skin temperature and oral temperature for both conditions, with the exception of oral temperature in the drinking condition. Aural temperature was significantly lower in the drinking condition ($p^b < .05$), but the fluid replacement did not attenuate the other measures of thermal state during the exposure. It is necessary to maintain blood supply to the skin and sweat rate in order to attenuate aural temperature during heat exposure. However, this is only possible when plasma volume is sufficiently maintained by replacing water lost as sweat.

![Figure 4.18: Drinking, 6 hrs post-exposure](image)

![Figure 4.19: Drinking, 6 hrs post-exposure](image)
4.4.2 Urinary measures

The preparation involved prior to the subjects taking part in each of the conditions was the same, and therefore presented an opportunity to assess the reliability of each of the measures in repeated conditions. Measures of $U_{osm}$, $U_{sg}$ and $U_{col}$ produced excellent results of reliability ($r > 0.9$), and $U_{vol}$ produced good results ($r > 0.8$). The sensitivity of measures was determined by comparing values pre- and post-exposure for the no drink condition, and a test of further sensitivity was to compare the post-exposure values of each of the conditions. $U_{osm}$, $U_{sg}$ and $U_{col}$ (and $U_{vol}$) were all shown to be the most sensitive measures to the process of dehydration. Figures 4.2 - 4.19 show the strong linear relationships between the two recognised measures of hydration state, $U_{osm}$ and $U_{sg}$, (Adolph, 1947; Armstrong et al, 1994; Francesconi et al, 1987; Tipton, 1982), and of $U_{col}$ with these two variables. This indicates that colour is a valid indicator of hydration state, as results correlate significantly with $U_{osm}$ and $U_{sg}$ both between and during experimental conditions, and confer with the findings of Armstrong et al (1994).

The reliability of $U_{vol}$ as a measure was shown to be good ($r > 0.8$), and it was also shown to be amongst the most sensitive measures of the process of dehydration. Although measures of $U_{vol}$ were found to be valid during the drinking condition ($p^b < .05$), they were not during the no drink condition. This may mean that a measure of $U_{vol}$ is an accurate way of monitoring hydration state when regular fluid replacement is possible, but not when a heat exposure dictates that fluid replacement is not possible. Since samples were given pre- and post-exposure, they represent timed samples (over 3 hours), which would be representative of urine collections during shift-work in an industrial setting.

When the body needs to conserve water, aldosterone is secreted, which increases reabsorption of sodium in the kidneys, so that water is retained at the same time. When aldosterone is secreted, it also encourages the secretion of potassium from the kidney. $U_K$ was shown to be a sensitive measure of hypohydration, and $U_K$ and $U_{Na}$ were shown to be valid in the drink condition. However, neither was shown to be a reliable measure of hydration state. Although $U_{temp}$ was shown to be sensitive to the
process of dehydration, it was neither reliable nor valid. $U_{ph}$ was found not to be a reliable, sensitive or valid indicator of hydration state.

4.4.3 Haematological measures

Overall, changes in hydration state were not accurately reflected in haematological indices (although haemoglobin was shown to be sensitive to an extent to the process of dehydration) because the body actively attempts to preserve the plasma volume by moving fluid from the intracellular to the extracellular space. These findings support those of Armstrong et al (1994), and the hypotheses of Francesconi et al (1987), which were: a) Plasma volume is defended by the body to maintain cardiovascular stability and plasma variables are unaffected until a threshold level of body weight loss (>3% body weight) has been achieved, and b) $U_{col}$, $U_{sg}$ and $U_{osm}$ are more sensitive indices of moderate hypohydration than are blood measurements.

4.4.4 Sweat measures

The subjects used in this experiment were not acclimated, so that in contrast to acclimated subjects, where electrolytes lost in sweat are modified (Sawka, 1992), sweat sodium increased throughout the heat exposure. $Sw_{Na}$ was a reliable and sensitive measure of hydration state during this study, but was found not be valid when correlated with widely recognised measures of hydration state, $U_{osm}$ and $U_{sg}$. $Sw_{K}$ was found not to be a reliable, sensitive or valid indicator of hydration state.

4.4.5 Subjective measures

There were no significant differences in feelings of thermal comfort or thermal sensation between the conditions, which may be expected under such environmental and exercise conditions. Subjects felt significantly thirstier in the no drink condition than the drinking condition only after cycle 5 ($p^b < .05$). This emphasises the discussions in Chapter 3 regarding thirst as an indicator for the need to intake fluids. By the time subjects felt significantly more thirsty in the no drink condition than the drinking condition, they had lost a mean of 2.324 litres of sweat.
4.4.6 Practicality of measures

Considering all the measures that were analysed, \( U_{\text{osm}} \), \( U_{sg} \) and \( U_{col} \) (and \( U_{vol} \) when fluid replacement is present) were all shown to be reliable, sensitive and valid indicators of hydration state. A summary of the reliability, sensitivity, validity and usability of each of the measures is provided in Table 4.7. This becomes especially convenient for the researcher, as each of the measures can be determined from one urine sample. The obvious ease of use of the colour scale renders it very practical during fieldwork monitoring hydration state of workers exposed to heat. Urine volume samples produced prior to and following shift work could represent timed samples. Each of these may also be used by the workers themselves to monitor their hydration state. The accuracy of both \( U_{\text{osm}} \) and \( U_{sg} \) make them appropriate tools for assessing the extent of hypohydration in a work setting by analysing collected urine samples in a laboratory setting (as long as they can be stored correctly in the meantime).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Reliability</th>
<th>Sensitivity</th>
<th>Validity</th>
<th>Usability</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_{col} )</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
</tr>
<tr>
<td>( U_{sg} )</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✔</td>
</tr>
<tr>
<td>( U_{osm} )</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>✔ ✔</td>
<td>X</td>
</tr>
<tr>
<td>( U_{temp} )</td>
<td>X</td>
<td>✔</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>( U_{\text{pH}} )</td>
<td>X</td>
<td>X</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>( U_{vol} )</td>
<td>✔</td>
<td>✔ ✔</td>
<td>✔</td>
<td>✔ ✔</td>
</tr>
<tr>
<td>( U_{Na} )</td>
<td>X</td>
<td>X</td>
<td>✔</td>
<td>X</td>
</tr>
<tr>
<td>( U_{K} )</td>
<td>X</td>
<td>✔</td>
<td>✔</td>
<td>X</td>
</tr>
<tr>
<td>Hct</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Hb</td>
<td>X</td>
<td>✔</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>( \text{Sw}_{Na} )</td>
<td>X</td>
<td>✔</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>( \text{Sw}_{K} )</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Thirst</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✔</td>
</tr>
</tbody>
</table>

Since thirst is well known to be an inefficient indicator of hypohydration and the need to intake fluids (Greenleaf, 1992), people that work in the heat require a reference to give them information about their current hydration state. Practical measures of monitoring hydration state are also necessary for research in field settings. The
measures of $U_{\text{osm}}$, $U_g$ and $U_{\text{col}}$ (and $U_{\text{vol}}$) have been shown to be accurate and practical solutions. In addition, some education and training may be required to increase awareness of the importance of regular fluid replacement, and to familiarise workers with the processes of monitoring their hydration state.

4.5 Conclusions

- Haematological indices do not accurately reflect hydration state.
- $S_{\text{Na}}$ was found to be a reliable and sensitive measure (although not valid), but it is certainly not a practical method for assessing hydration state.
- $U_{\text{osm}}$, $U_g$ and $U_{\text{col}}$ (and $U_{\text{vol}}$) were found to be practical, reliable, sensitive and valid methods of assessing hydration state.
- $U_{\text{vol}}$ and $U_{\text{col}}$ may be used by workers themselves, as they are practical and straightforward.

Endnote

In addition to the techniques describe in this chapter a further method of determining hydration state warrants investigation. This is the BIA technique, and since it requires a different approach, its use is considered in the next chapter.
Chapter 5
Chapter 5

AN EXPLORATORY STUDY INTO THE USE OF THE MULTI-FREQUENCY BIOELECTRICAL IMPEDANCE ANALYSIS TECHNIQUE TO PREDICT THE AMOUNT OF TOTAL BODY WATER AND EXTRACELLULAR WATER FOR EXERCISING ADULTS IN HOT CONDITIONS

5.1 Introduction

Chapter 3 considered the use of thirst as an indicator of the need to intake fluids, and concluded that it was not suitable. Other measures or indicators were then investigated for their reliability, sensitivity, validity and practicality as measures of hydration state in Chapter 4. This chapter explores a different approach to determine body water needs: the Bioelectrical Impedance Analysis (BIA) technique. By the end of the chapter, it is hoped that the technique can be judged and represented in a similar manner to the other considered measures, as in Table 4.7. This chapter aims to determine the usefulness of the BIA technique, in terms of accuracy and practicality, for subsequent studies involving work in hot environments.

Bioelectrical impedance analysis (BIA) is a straightforward, portable, non-invasive technique, which can be used for the measurement of the amount of extracellular water (ECW) and total body water (TBW). Since its development, it has become a popular method for assessing body composition (Kushner et al., 1992; Lukaski et al., 1985; Segal et al., 1985). The BIA technique involves applying a small alternating current to the body, normally at a frequency of 50 kHz, and the resistance or impedance of the body to that current is measured. As only water with dissolved electrolytes is able to conduct the current, the resistance or impedance of the body to that current is a measure of body water content (Lukaski, 1987). The method is based on the principle that impedance to the electrical flow of a localised injected current is related to the square of the length of the conductor (approximated by height) (BI index = height$^2$/impedance) (Segal et al., 1991), and therefore, impedance to that current is
inversely proportional to the amount of body water (Deurenberg et al, 1995a). The prediction equation may also include other parameters such as weight and age.

5.1.1 BIA measurement

In order to conduct a BIA measurement, four electrodes are connected to the body (see method for more detail). As the cell membrane behaves as an electrical capacitor, alternating currents at low frequency are not able to penetrate the cell. Therefore, at low frequency (eg. 5 kHz), the impedance of the body is a measure of ECW. At such low frequencies, BIA is only able to predict TBW in healthy subjects because of the close correlation between extracellular volume and TBW in these subjects. The prediction error for TBW from BIA measurements is 1.5 – 2.5 kg, that is, a precision of about 5%, and about 1kg for ECW (Deurenberg et al, 1995b; Segal et al, 1991). However, with increasing frequency the reactance of the cell membrane decreases and finally disappears (Deurenberg et al, 1996). Thus, at very high frequency (eg. 200 kHz), impedance is a measure of TBW (Jenin et al, 1975; Thomasset, 1962). The development of instruments that can measure impedance at different frequencies (multi-frequency analysers) has therefore allowed the independent estimation of ECW and TBW.

5.1.2 Alternative techniques

In addition to BIA, several other techniques for the assessment of body composition have been developed, such as neutron-activation analysis (Burkinshaw, 1987), computed tomography and NMR imaging (Heymsfield, 1987) and total body electrical conductivity (TOBEC) (Presta et al, 1983; Van Loan et al, 1987). However, densitometry (underwater weighing) (Deurenberg et al, 1989) and isotopic dilution techniques are considered to be the reference methods for measurements of total body water (Gleichauf and Roe, 1989; Jebb and Elia, 1991). Dilution techniques (discussed in detail in Chapter 10) use marker substances that distribute in a specific body fluid compartment. However, dilution techniques are frequently inappropriate, particularly in a clinical or practical setting, due to the complexity of the analysis and the difficulties in making repeated measures over short periods. Also, the limits on the precision of water dilution measurements are of the order of 1-
2% (Coward et al, 1988), which means it is difficult to use this technique to accurately measure changes in TBW of less than 1-2 L (Jebb and Elia, 1991).

5.1.3 Advantages of the BIA technique

The BIA technique clearly has advantages over the other methods of assessing body composition already discussed: the latter tend to be expensive, complex, invasive and time consuming (Borghi et al, 1996; Hannan et al, 1995), whereas BIA is relatively inexpensive, battery chargeable, portable, safe, non-invasive, requires little subject cooperation, and gives rapid results (Gleichauf and Roe, 1989; Hegarty et al, 1998). This has provoked a great deal of interest and subsequent research into the validity and sensitivity of BIA as a tool to estimate ECW and TBW. However, as Scalfi et al (1999) report, contrasting results have been reached so far on the use of BIA in assessing body composition changes.

The reliability of test re-test impedance measures has been examined and confirmed by several investigators (Lukaski et al, 1985; Segal et al, 1985; Ward et al, 1997), as has the accuracy of the impedance technique for determining body composition: high correlation coefficients have been reported between body composition estimates determined by bioelectrical impedance and reference methods (such as densitometry and dilution techniques) (Kushner Schoeller, 1986; Kushner et al, 1992; Lukaski et al, 1985, 1986; Segal et al, 1985). These studies investigated the bioimpedance technique under static conditions.

5.1.4 Disadvantages of the BIA technique

In contrast, a number of investigators have raised questions about the validity of the bioimpedance technique, for both static measures and changes in body composition. Forbes et al (1992) raise doubts about the applicability of the basic equation to evaluate changes in body composition, and suggests that the bioimpedance technique offers no advantage over body weight in predicting body composition changes induced by diet or by diet plus exercise.

Jebb and Elia (1991) conducted a study on renal patients receiving dialysis, where rapid changes in body water can be quantified, in order to investigate the sensitivity of
the bioimpedance technique to changes in body water. They found that although the regression lines of the plot of change in height/impedance versus loss of fluid for each subject had high correlation coefficients, there was a four-fold variation in the slopes of the different curves. In addition, the total change in body water, calculated by a variety of prediction equations (including that provided by the manufacturer), over-estimated the loss of fluid by a mean of between 86-100%. One of the possible explanations put forward for the wide variation between subjects and the over-estimation of body water loss by prediction equations pertains to the assumptions of the basic equation. The formula used to relate changes in impedance to changes in total body water assumes that the specific resistivity (specific impedance) of the conducting fluid is constant. However, if there were differences in the specific resistivity of the conducting fluid, or if such changes were brought about by dialysis as a result of changes in the concentration of intra- or extra-cellular substances, then the relationship between height/impedance and total body water will vary. This is in agreement with Gleichauf and Roe (1989), who found that changes in body weight associated with sodium intake explained a significant proportion of error in resistance measures. This may also be the case for subjects who have lost body water and electrolytes through sweating.

Another reason for such reported inconsistencies (Jebb and Elia, 1991) may be due to the site of water loss. It has been shown that the trunk, which contributes 46% to body weight, accounts for only 10% of whole body impedance (Fuller and Elia, 1989). Hence, even large changes in fluid from the trunk would be expected to have only a small effect on total body impedance. Conversely, fluid removed from the limbs will have relatively greater effect on the whole body impedance, since the arms and legs (8% and 34% of body weight) account for 46% and 44% of total body impedance, respectively.


A further issue is that prediction formulas have been shown to be population specific, and an equation developed in one population can therefore result in inaccurate
estimates when applied to another population. For example, the elderly (Svendsen et al, 1991), the lean or obese (Steijaert et al, 1997), and cardiac and pulmonary patients (Katch et al, 1986).

5.1.5 The use of BIA for measuring humans during heat-exercise

To the author’s knowledge, there is no literature that relates to the effective use of the BIA technique in measuring changes in body water in subjects who may be dehydrating or hypohydrated and experiencing heat strain in situ. This may be due to the fact that resistance has been shown to decrease when skin is warmed (Caton, 1988). One study (Saunders et al, 1998) compared BIA and hydrostatic measures in endurance trained athletes following exercise in the heat. They also considered the effects of the ionic content of rehydration solutions on BIA measures. Since the BIA measures took place 40-45 minutes after exercise or fluid ingestion, and after the hydrostatic weighing, it is likely that body temperature had lowered significantly when the BIA measures took place. Regardless of this point, the athletes exercised until they had lost approximately 3% of their body weight, so that they were in an abnormal state of hydration. The principle of hydrostatic weighing is based on equations that assume normal hydration; these subjects were not in a normal state of hydration. The changes in hydration caused large fluctuations in BIA fat weights, and the authors concluded that these changes could be interpreted incorrectly as changes in body fat content. They also found that the electrolyte content of the hydrating solution did not have any effect on the BIA measures, and concluded that this was because the subject had measures taken 40-45 minutes after fluid ingestion. This, according to Matthews and Gilker (1995), was likely not enough time for the ingested fluid to equilibrate into the intracellular and interstitial pools (it should take approximately 2 hours).

The user’s guide supplied with the Bodystat Multiscan 5000, which was used in this experiment, states that... 'when using a single frequency unit, the following pre-test protocols are recommended. However, in the multi-frequency environment, it is unlikely that these necessarily apply, but are given for information purposes:
- for accurate and reproducible results, it is very important that the subject is as normally hydrated as possible
- no eating or drinking 4-5 hours prior to the test
- no alcohol or caffeine consumption 24 hours prior to the test
- do not perform a test after strenuous exercise; the body would have lost excessive fluid through sweating and an abnormally low fluid level would thus increase the impedance measurement, resulting in an artificially high fat percentage
- the skin should be at normal body temperature and should not be sweating...

No separate guidelines are given for use with the multi-frequency system. It seems that the cautionary notes apply to estimation of body composition from body water content, rather than estimating body water from impedance. However, if the above pre-test protocols were to apply, it is highly likely that this technique would not be suitable for both laboratory heat strain / exercise studies, and field work, which may for example involve monitoring firefighters carrying out training activities or working operationally.

Therefore, in light of the controversy surrounding the technique, a small-scale investigative study was carried out in order to determine if the BIA technique could be a useful measure in this laboratory’s particular work. That is, in determining changes in body water during and immediately following physical work in a heat chamber. Inferences would then be made as to the technique’s appropriateness in a field setting.

5.2 Method

5.2.1 Subjects

Two male subjects took part in the one-day study. The study took place in the Human Thermal Environments Laboratory (HTEL) at Loughborough University. Subjects completed HTEL and Loughborough University health screen questionnaire (Appendix I) before experimental work commenced. The BIA technique and procedure was explained to the subjects and anthropometric measures were also taken prior to the experiment.
Anthropometric measurements of height and weight were taken (according to the equipment and techniques described in Section 2.2.1), and subject age was also noted. For Subject 1 these were: height of 178.5 cm; weight of 84.316 kg; and age of 46 years, and Subject 2: height of 172.0 cm; weight of 71.534 kg; and age of 43 years.

5.2.2 Experimental design

The experiment took place on one day, and compared changes in BIA measures of a subject (Subject 1) throughout a period of exercise and heat exposure with those of an individual (Subject 2) at rest in a moderate environment. The length of the heat exposure was 1 hour 20 minutes, but measures were taken before and after this period.

5.2.3 Conditions

The environmental conditions in the thermal chamber during the heat exposure were: air temperature (mean ± SD): 40.3 ± 1.0 °C, and relative humidity: 31.3 ± 1.6 %. The conditions of the moderate environment were (mean ± SD): 19.6 ± 0.8 °C, and relative humidity: 58.4 ± 2.1 %. Subjects consumed 0.75 litres of fluid 2 hours prior to the experiment, but consumed nothing in the hour prior to the first measure.

5.2.4 Clothing

Subject 1 wore only shorts and training shoes (the right training shoe was removed for BIA measures). An impermeable chemical protective jacket was donned during Exercise 3 in order to increase sweating. Subject 2 wore a shirt, jeans, socks, underwear and shoes (the right shoe and sock were removed during BIA measures).

5.2.5 Measurements

Subject 1’s $T_{aus}$ and HR were measured every minute during the heat exposure using the equipment and techniques described in Section 2.2.3. Weight in shorts and trainers was taken as a baseline measure upon entry to the chamber, after every exercise set, upon exiting the chamber, and at several intervals following the heat exposure. Subject 2’s weight was taken as a baseline measure and 60 minutes after the heat exposure took place.
BIA was performed using the Bodystat Multiscan 5000 (Bodystat, Isle of Man, UK) analyser. Height, weight, age, sex and activity level were input to the analyser prior to any BIA measures. Subjects removed their right shoe (and sock in the case of Subject 2), and lay supine with the arms and legs spread slightly so that no body parts were touching one another. Self-adhesive disposable electrodes (Bodystat, Isle of Wight, UK) were placed at four sites on the right hand side of the body to avoid the battery current passing through the side of the body where the heart is situated. Two injection electrodes were placed on the dorsal surfaces of the hand and foot, and two sensor electrodes between the lateral and medial malleoli of the ankle and between the distal prominences of the ulna and radius according to the method of Lukaski et al (1985) and the manufacturer. Leads were then plugged into the analysing unit and connected by crocodile clips to the electrodes on the skin. Subjects lay in the supine position for 5 minutes before any test was carried out. For each test, three measurements were taken and the average was given as the result.

5.2.6 Experimental procedure

A baseline BIA measure was taken for both subjects immediately prior to the heat exposure. Subject 1 then entered the thermal chamber and a further BIA measure was taken. Subject 1 completed a set of five exercises during the heat exposure in the thermal chamber. Every exercise lasted 10 minutes, in between each of which was a five minute rest break, when weight and BIA measures were taken. The exercises carried out during the heat exposure were:

- Exercise 1 Treadmill run at 4.1 mph
- Exercise 2 Cycle at 65 rpm (cradle plus 1 kg)
- Exercise 3 Step at 83 foot movements per minute (step height: 15 cm)
- Exercise 4 Treadmill run at 6 mph
- Exercise 5 Cycle at 70 rpm (cradle plus 1 kg)

Subject 2 remained outside the thermal chamber, did not carry out any activity during this time, and was only weighed once more, which took place 60 min after the heat exposure. Following the heat exposure, Subject 1 observed the protocol detailed in Table 5.1.
Table 5.1: Protocol observed by Subject 1 following BIA test heat exposure

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Time after exiting chamber (hr:min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Showered &amp; dried off, re-dress, BIA measure</td>
<td>01:10</td>
</tr>
<tr>
<td>Drank 250 ml water</td>
<td>01:18</td>
</tr>
<tr>
<td>Drank 250 ml water</td>
<td>01:20</td>
</tr>
<tr>
<td>Drank 250 ml squash*</td>
<td>01:23</td>
</tr>
<tr>
<td>BIA measure</td>
<td>01:30</td>
</tr>
<tr>
<td>Weigh subject</td>
<td>01:35</td>
</tr>
<tr>
<td>Drank 250 ml squash*</td>
<td>01:37</td>
</tr>
<tr>
<td>BIA measure</td>
<td>01:44</td>
</tr>
<tr>
<td>Weigh subject</td>
<td>01:47</td>
</tr>
</tbody>
</table>

* the squash was an orange and pineapple flavoured solution with 0.2 % carbohydrate and 22.6 mmol.L⁻¹ NaCl

5.3 Results

The physiological responses and BIA measurements taken from Subject 1 during the heat / exercise exposure and in the events that followed are shown in Table 5.2.

5.3.1 Total weight

Total weight as recorded with weighing scales (actual weight) and total weight as given in the BIA readings were plotted throughout the experiment for Subject 1 (Figure 5.1). Subject weight was initially entered into the BIA software, and from that point onwards, the BIA technique predicted total weight from the changes it detected in impedance. At all points following entry to the hot environment there are large discrepancies between the two total weight values. The BIA weight value actually increased slightly between entry to the hot environment and the end of Exercise 1, even though sweating took place and the weighing scales recorded a loss in body weight of 0.142 kg. Values given in the BIA analysis from this point onwards remained constant, despite that fact that a total of 1.652 litres of sweat was lost, and then 1 litre of fluid was consumed. The BIA readings failed to detect any of these changes.
Figure 5.1: Actual total body weight (weighing scales) and BIA measures of total body weight plotted throughout the experiment. (Nb: the events noted on the x-axis are not of equal interval)
Table 5.2: Physiological responses and BIA measures of Subject 1 during the heat / exercise exposure

<table>
<thead>
<tr>
<th>Procedure and stopwatch time</th>
<th>Time of BIA</th>
<th>Right aural temp °C</th>
<th>Left aural temp °C</th>
<th>Heart rate bpm</th>
<th>Actual Total wt kg</th>
<th>BIA Total wt kg</th>
<th>TBW litres</th>
<th>ECW litres</th>
<th>ICW litres</th>
<th>Impedance values 5 kHz Ohms</th>
<th>Impedance values 200 kHz Ohms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base-line</td>
<td>-00:06</td>
<td>-00:06—00:05</td>
<td>37.0</td>
<td>36.8</td>
<td>73</td>
<td>84.316</td>
<td>84.3</td>
<td>42.7</td>
<td>19.6</td>
<td>23.1</td>
<td>552.6</td>
</tr>
<tr>
<td>Enter heat</td>
<td>-00:02</td>
<td>-01:00—00:00</td>
<td>37.0</td>
<td>36.8</td>
<td>76</td>
<td>84.298</td>
<td>84.3</td>
<td>42.83</td>
<td>19.8</td>
<td>23.03</td>
<td>543.3</td>
</tr>
<tr>
<td>Start Ex 1</td>
<td>00:00</td>
<td>-</td>
<td>37.0</td>
<td>36.8</td>
<td>79</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>End Ex 1</td>
<td>00:10</td>
<td>14:00—15:00</td>
<td>37.4</td>
<td>37.4</td>
<td>139</td>
<td>84.156</td>
<td>84.4</td>
<td>43.7</td>
<td>20.2</td>
<td>23.5</td>
<td>521.3</td>
</tr>
<tr>
<td>Start Ex 2</td>
<td>00:15</td>
<td>-</td>
<td>37.4</td>
<td>37.4</td>
<td>104</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>End Ex 2</td>
<td>00:25</td>
<td>29:00—30:00</td>
<td>37.8</td>
<td>37.8</td>
<td>128</td>
<td>83.971</td>
<td>84.4</td>
<td>42.53</td>
<td>19.7</td>
<td>22.83</td>
<td>546</td>
</tr>
<tr>
<td>Start Ex 3</td>
<td>00:30</td>
<td>-</td>
<td>37.6</td>
<td>37.6</td>
<td>101</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>End Ex 3</td>
<td>00:40</td>
<td>44:00—45:00</td>
<td>37.6</td>
<td>37.6</td>
<td>114</td>
<td>83.747</td>
<td>84.4</td>
<td>42.56</td>
<td>19.7</td>
<td>22.86</td>
<td>550</td>
</tr>
<tr>
<td>Start Ex 4</td>
<td>00:45</td>
<td>-</td>
<td>37.6</td>
<td>37.6</td>
<td>98</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>End Ex 4</td>
<td>00:55</td>
<td>59:00—01:00</td>
<td>38.2</td>
<td>38.2</td>
<td>171</td>
<td>83.502</td>
<td>84.4</td>
<td>43.1</td>
<td>20</td>
<td>23.1</td>
<td>532.6</td>
</tr>
<tr>
<td>Start Ex 5</td>
<td>01:00</td>
<td>-</td>
<td>38.4</td>
<td>38.4</td>
<td>124</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>End Ex 5</td>
<td>01:10</td>
<td>01:14—01:15</td>
<td>39.0</td>
<td>39.0</td>
<td>156</td>
<td>83.262</td>
<td>84.4</td>
<td>42.8</td>
<td>19.9</td>
<td>22.9</td>
<td>538.3</td>
</tr>
<tr>
<td>Exit heat</td>
<td>01:15</td>
<td>-</td>
<td>38.8</td>
<td>38.8</td>
<td>-</td>
<td>83.186</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Shower, dry</td>
<td>02:25</td>
<td>02:24—02:25</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>84.4</td>
<td>41.83</td>
<td>19.23</td>
<td>22.6</td>
<td>576</td>
<td>437</td>
</tr>
<tr>
<td>Weigh</td>
<td>02:27</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>82.588</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Drank 250 ml water 02:33</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Drank 250 ml water 02:35</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Drank 250 ml squash 02:38</td>
<td>02:44—02:45</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>84.4</td>
<td>41.46</td>
<td>19.06</td>
<td>22.4</td>
<td>586.6</td>
<td>446</td>
</tr>
<tr>
<td>Weigh</td>
<td>02:50</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>83.356</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Drank 250 ml squash 02:52</td>
<td>02:58—02:59</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>84.4</td>
<td>41.26</td>
<td>18.86</td>
<td>22.4</td>
<td>597</td>
<td>451</td>
</tr>
<tr>
<td>Weigh</td>
<td>03:02</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>83.613</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* 38:00 - donned chemical protective jacket (impermeable) (weights are corrected)
5.3.2 Impedance values and body weight change

Due to the apparent insensitivity of the BIA readings to detect change in total body weight, actual body weight (weighing scales) is used in the following analysis. Impedance values were plotted against actual cumulative body weight change for Subject 1 (Figure 5.2). Impedance values at both frequencies first decreased and then increased, despite the fact that body weight loss was taking place throughout this period. This immediate decrease in impedance coincides with the immediate increase in total body weight recorded by the BIA (which was contradictory to actual total body weight recorded), as discussed in Section 5.3.1. Impedance at both frequencies then increased as body weight was lost through sweating, yet continued to rise when sweat loss ceased and fluid was ingested.

![Figure 5.2: Actual cumulative body weight change versus impedance at 5 kHz and 200 kHz. The data points represent the intervals at which the subject was weighed and BIA measured](image)

5.3.3 Weight and body water changes

Values of actual body weight change (weighing scales), BIA TBW change and BIA ECW change were plotted throughout the experiment for Subject 1 (Figure 5.3). In circumstances where a subject is exercising in a hot environment and sweating profusely, change in weight is likely to be a good indicator of change in TBW and ECW. However, the three sets of data were dramatically different: as actual body weight decreased at a steady rate throughout the heat and exercise sojourn, BIA
values of TBW and ECW increased and decreased erratically. Although BIA measures of TBW and ECW did tend more towards zero once fluid intake began, they were nevertheless recorded as losses.

Figure 5.3 Values of actual body weight change (scales), BIA TBW change and BIA ECW change plotted throughout the experiment (Nb: the events noted on the x-axis are not of equal interval)

5.3.4 Subject 2
As Subject 2 was inactive in a moderate environment for the duration of the test, the only occasions weighing took place were for a baseline measurement (at the same time as Subject 1) and one hour after Subject 1 ceased exercise in the hot environment. The change in actual weight and the readings from the BIA analysis for Subject 2 are shown in Table 5.3. A small amount of weight loss (0.146 kg), probably due to respiration, took place throughout the experiment, but this was not detected in the BIA measures. However, as body weight was lost, TBW and ECW compartment values decreased slightly, and impedance increased slightly at both frequencies.
Table 5.3: Change in actual weight and BIA values given for Subject 2

<table>
<thead>
<tr>
<th></th>
<th>Total weight Actual kg</th>
<th>Total weight BIA kg</th>
<th>TBW litres</th>
<th>ECW litres</th>
<th>Impedance values 5 kHz Ohms</th>
<th>Impedance values 200 kHz Ohms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>71.534</td>
<td>71.5</td>
<td>39.7</td>
<td>18.5</td>
<td>528.3</td>
<td>401</td>
</tr>
<tr>
<td>End Ex 1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>531.3</td>
<td>403.3</td>
</tr>
<tr>
<td>End Ex 2</td>
<td>-</td>
<td>71.5</td>
<td>39.6</td>
<td>18.4</td>
<td>532</td>
<td>404</td>
</tr>
<tr>
<td>End Ex 3</td>
<td>-</td>
<td>71.5</td>
<td>39.43</td>
<td>18.3</td>
<td>537.3</td>
<td>406.6</td>
</tr>
<tr>
<td>End Ex 4</td>
<td>-</td>
<td>71.5</td>
<td>39.33</td>
<td>18.3</td>
<td>541.6</td>
<td>410</td>
</tr>
<tr>
<td>End Ex 5</td>
<td>-</td>
<td>71.5</td>
<td>39.26</td>
<td>18.2</td>
<td>544.3</td>
<td>411.3</td>
</tr>
<tr>
<td>1 hr post test</td>
<td>71.388</td>
<td>71.5</td>
<td>39.4</td>
<td>18.3</td>
<td>541.3</td>
<td>408.6</td>
</tr>
</tbody>
</table>

5.4 Discussion

It was clear from the study that there are some difficulties in using the BIA measuring technique as an accurate method of quantifying changes in body weight and body fluid compartments when a person carries out physical work in a hot environment.

Change in total body weight was measured with BIA and also using scales, yet the values obtained were very dissimilar. The BIA values remained almost constant, despite the fact that profuse sweating took place, followed by fluid intake. Also, BIA measures for TBW and ECW did not reflect the sweat loss that took place during work in the heat, yet it is ECW that provides the precursor fluid for sweat. Further, the BIA measures of TBW and ECW failed to detect the 1 litre of fluid taken on board later in the experiment. It is likely that an intracellular water (ICW) measure would not register this event (which was the case here), as it takes approximately 2 hours for the ingested fluid to equilibrate into the intracellular and interstitial pools (Matthews and Gilker, 1995). However, in this case, there was approximately 30 minutes between the first fluid ingestion and the last BIA measure, and in this time some gastric absorption will have taken place, and therefore should have been identified in the TBW and ECW measures, and before that when fluid was in the stomach in the TBW measures. Both values fell during the time in which fluid was consumed.
In Figure 5.3, there was a peak in BIA ECW following Exercise 1, and a further, smaller, peak after Exercises 4 and 5. The fact that these peaks were present, even though sweat was being lost, may have been explained by a shift in water from the intracellular to the extracellular compartment, in order to sustain sweating. However, no losses were recorded in the ICW compartment at these times; in fact the opposite occurred. Also, it is not likely that the subject had produced enough sweat (either in total or at any of these points) to induce such a shift in body water.

As dehydration takes place, impedance values are expected to increase, as the volume of conducting fluid available has decreased. In Figure 5.2, impedance values dropped at both frequencies until after Exercise 2, even though sweat loss had begun. Following Exercise 3, impedance values at both frequencies decreased until the end of the heat exposure. Values at the 5 kHz frequency were actually lower at the end of the heat exposure than at the beginning, and those at the 200 kHz frequency were approximately the same. If there had been a rise in impedance values at the 200 kHz frequency (where the electrical signal is able to penetrate the cell membrane), and vice versa at the 5 kHz frequency (where the electrical signal cannot penetrate the cell membrane), a transfer of water from the intracellular to the extracellular compartments may have taken place. However, there was no such change in either the impedance values or the ECW and ICW compartments. It is likely that the subject continued sweating once the heat exposure and exercise had ceased, as body weight decreased by a further 0.598 kg in the 72 minutes that followed. Impedance values increased markedly during this time and thereafter. This change of direction in impedance values may indicate that a subject must lose a certain amount of body water in order to affect the BIA reading, or may be a result of measuring a neutral, non-sweating subject, since resistance has been shown to decrease when skin is warmed (Caton et al., 1988).

The formula used to relate changes in impedance to changes in total body water assumes that the specific impedance of the conducting fluid is constant. However, if there were differences in the specific impedance of the conducting fluid, which is entirely likely considering the subject lost 1.652 kg of sweat, then the relationship between height²/impedance and total body water will vary. This is in agreement with Gleichauf and Roe (1989), who found that changes in body weight associated with
sodium intake explained a significant proportion of error in resistance measures. Correcting for electrolytes lost in sweat would not only prove impractical, but also possibly inaccurate, since different sites of the body contribute exceptionally varying amounts to total body impedance (Fuller and Elia, 1989). Hence, the site at which sweat and electrolytes were produced would be of extreme importance as to the extent of the effect on impedance. Therefore, it seems unlikely that the equations that provide the basis for BIA are applicable in the environment used in this study.

Although the BIA technique did not detect the slight weight change in Subject 2, who was not exercising or exposed to heat, it did record slight decreases in both TBW and ECW. In turn, it also recorded slight increases in impedance at both frequencies throughout this body water loss, which was to be expected, as the volume of conducting fluid available had decreased. However, with such small changes, it is difficult to conclude that the technique was definitely successful for this subject.

The users' manual for the Bodystat Multiscan 5000 stated that the pre-test protocols that should be adhered to for single frequency testing were unlikely to apply in the multi-frequency environment. One of these protocols was that the subject should be as normally hydrated as possible, and another was that the skin should be at normal body temperature and should not be sweating. As stated earlier, these precautions are more likely to be aimed at body composition, and therefore body water changes should be reflected in changes in impedance.

5.5 Conclusions

During this study, the BIA measuring technique was not sensitive to changes either in total body weight or body composition, when a subject was hot, physically active and dehydrating. However, the technique was sensitive to those changes when a subject was neutral, sedentary and normally hydrated, but the changes were so small that no conclusions can be drawn from this. This preliminary study suggests that more work is needed on reliability, sensitivity, validity and also calibration procedures to determine the usefulness of this technique as a practical application.
5.1 Summary of Part II

The findings of Part II, Methods of Assessing Hydration State, were as follows:

- Chapter 3 described the sensation of thirst and how it can be measured, as well as the concept of voluntary dehydration, which occurs when sufficient fluids are available but not consumed. Thirst was not, therefore, considered to be an accurate method of controlling or monitoring hydration state, and further measures were necessary.

- The aim of Chapter 4 was to investigate other methods, in addition to thirst, of measuring hydration state in terms of reliability, sensitivity, validity and practicality. The measures that were found to be most accurate were $U_{\text{col}}$, $U_{\text{osm}}$ and $U_{\text{eg}}$ (and $U_{\text{vol}}$ to a lesser extent), and of those, $U_{\text{col}}$ and $U_{\text{vol}}$ were thought to be particularly valuable in terms of their practicality.

- Chapter 5 was a small-scale investigation, which aimed to determine the value of the BIA technique in terms of accuracy and practicality. The results of the study suggested that further work is required before this can be established.

- Overall, Part II investigated a number of techniques that may be used to monitor hydration state, and which may vary in the manner in which they are manifested, their complexity and invasiveness. The outcome of the section is the identity of several tests, which were found to be accurate and practical, and which therefore can be applied in subsequent field and laboratory studies as methods for determining water requirements.
Part III

A Case Study:

The Fire Service
PART III: A CASE STUDY: THE FIRE SERVICE

The aims of this section of the thesis are to: 1) apply the information produced in Part I and the measures developed in Part II in a practical setting where a hydration problem has been identified i.e. in the Fire Service; 2) determine the areas and extent of the problem; and 3) to identify a solution to the problem using the techniques developed in Parts I and II.
Chapter 6
Chapter 6

THE FIRE SERVICE: ISSUES OF HEAT STRESS AND DEHYDRATION

6.1 Introduction

Part III covers a case study carried out with three fire brigades, in order to identify if dehydration is a problem within this service industry and to what extent. This chapter aims to provide background information on the Fire Service and to outline the particular aspects of work that are affected by heat stress and dehydration. This will provide a context within which an effective drinking regime can be developed.

Firefighting has long been associated with high physiological demand, but firefighters are not usually exposed to extreme environments everyday. So although there is a risk of heat stress and dehydration when firefighters attend a fire incident, this series of experiments concentrates on the heat exposure of firefighters during training. Exposing firefighters to the conditions they might expect at a fire incident is called hot fire training. This takes place in a firehouse, which is a building specifically constructed for the purpose of hot fire training, and is situated on a fireground. During hot fire training, there are two groups of people exposed to the heat: the fire training instructors and the firefighter recruits (or qualified firefighters if they are taking part in continual training). During their training, firefighter recruits are given one week's intensive self-contained breathing apparatus (SCBA) instruction, at the end of which they use SCBA in the firehouse. Following this training, they must take part in heat and smoke training at least four times per year during their operational career. Fire training instructors, however, can be exposed to extreme heat on a daily basis, often several times per day, as it is their job to provide instruction in the firehouse to all recruits that pass through. The fire training instructors escort and instruct recruits in hot, humid and often polluted atmospheres, and both groups incur great levels of physiological stress (Faff & Tutak, 1989; Lemon & Hermiston, 1977; O'Connell et al, 1986).
6.2 Firehouse Design and Layout

A firehouse is a building specifically constructed for hot fire training. In a traditional firehouse there is always a crib room on the ground floor, which is where the fire is lit to provide heat and smoke throughout the building. The crib room contains a large cage in which wooden pallets, straw and paper are burnt. There are vents and chimneys in the crib room that transfer heat and smoke to all other rooms in the firehouse. The air temperature is monitored throughout a firehouse, and this is registered in an adjacent control room. If the instructor in charge deems that the temperature is too high, he will activate a siren and the lights will come on in the firehouse; all instructors and recruits will then vacate the firehouse immediately. Firehouses also have the capacity to simulate flooding.

There are usually three floors in a firehouse, but the firefighter recruits only enter the first and second floors. The specific layout of each firehouse is different, but in order to present as many search scenarios as possible, all simulate rooms of a house, balconies, and larger rooms that represent warehouses. There are items such as wardrobes and beds, which must be searched thoroughly by the recruits. The walls are blackened, and there is no lighting for the duration of training. The doors in the firehouse are randomised, so that some open on the left and others on the right, and some are push, whereas others are pull. The staircases also present a problem to the recruits: the treads and rises are different lengths, and often change across a step.

In recent years firehouses have been designed differently. The new firehouses provide a greater scope of scenarios, and recruits can tackle attic fires, roof fires and use trap doors in addition to the usual rooms in a firehouse. Rather than have a crib room, which provides heat and smoke for the whole building, each room has the capacity to have its own fire. These can be either carbonaceous or liquid petroleum gas (LPG) fires. The carbonaceous fires take the form of a small cage containing burning wood. A sprinkler system can be activated in the control room to extinguish the carbonaceous fires. There are a range of gas burning systems available to enable the creation of various fire types and scenarios. The gas systems are operated from the control room; they utilise pilot lights, and the gas supply can be removed immediately. Flame height and intensity can be varied, as can air supply via extractor.
fans. Shielded air temperature is recorded at one and two metre heights throughout the firehouse. A further feature of the control room is a tracking system available to monitor the movements of all instructors and recruits within the firehouse.

At the National Fire Training School (Morton in the Marsh, UK), where all firefighter recruits attend following their initial training, there are also separate fire ‘sheds’. These are large rooms that contain carbonaceous fires, which the recruits must extinguish as quickly and safely as possible.

6.3 Procedures in the firehouse

6.3.1 The Job of a Fire Training Instructor

During recruit training in firehouses the fire training instructors must ensure the safety of the inexperienced recruits, and being fully aware of their positioning and actions in the firehouse is crucial. Throughout a day of fire training the recruits usually enter the firehouse two or three times during the day, for approximately fifteen to thirty minutes each time, in groups of three or four. There may be two or three groups in at a time, and the session continues until the whole class of recruits has been in the firehouse. However, the fire training instructors are required to be in the firehouse for the entire session, which can last for 2-3 hours, and are exposed to extremely high temperatures. Tasks carried out by the fire training instructors include: laying a safety line for recruits to follow; positioning dummies (30-70 kg) in set locations for rescue; tracking recruits throughout the firehouse; aiding them with dummies and fire hoses; calculating cylinder times to ensure that recruits have determined this correctly; and occasionally dragging recruits to safety, should they endanger themselves. Whilst observing the recruits, the instructors usually stand in the coolest part of the room, and often kneel or crouch to avoid heat stress. In addition, one or two of the instructors are required to ‘stoke’ the fire (build up and maintain) before and throughout the session, exposing these individuals to the highest temperatures. Due to time constraints, often only very short breaks are taken between sessions.

During training at the Fire School where recruits extinguish fires, as described in Section 6.2 the training instructors remain at the back of the room and observe the recruits’ actions. They are required to intervene if a recruit places himself in danger,
and / or is showing any signs of heat strain. In this case, the fire instructor removes the recruit from the building as soon as possible.

6.3.2 Procedure for Firefighter Recruits

During firefighter training, recruits attend purpose built firehouses, in which they experience high ambient temperatures, smoke, flooding and casualty rescue. As mentioned in Section 6.3.1 firefighter recruits usually enter the firehouse two or three times during a day of hot fire training. They enter the firehouse in groups of three or four, and each exposure lasts approximately fifteen to thirty minutes. Each member of the group calculates their cylinder time on a board prior to entering the firehouse, so that colleagues are aware when each recruit should exit the firehouse. The recruits then enter the firehouse, with a fire hose, following the safety line, which has been laid down previously by the instructors. The purpose of the safety line is to provide a means of retreat from the firehouse; a recruit can attach a separate line to the safety line if they wish to search several metres either side of the safety line. The firefighter recruits are taught how to search a dark, smoke filled room prior to entering the firehouse. They must remain attached to the safety line at all times, be aware of each others actions, and between the group, they must search under any beds, along all walls, and in / on top of any cupboards and wardrobes. Their task is to retrieve all the dummies that have been placed in the firehouse as quickly as possible. They are not told how many there are, and therefore must conduct a thorough search of every room. The recruits exit the firehouse when they have searched all rooms or when their cylinders run low, whichever is sooner.

6.4 Work Time Limits

Safety precautions would dictate the designation of maximal permissible limits for work duration. However, each real fire scene presents unique problems and it is very difficult to take into account all the variables influencing the thermal environment so as to predict precisely the limiting working time. As a result, a schedule of work and rest during firefighting is most often based on subjective feelings of fatigue and overheating (Faff & Tutak, 1989), as well as cylinder time. This method of working is transferred to training, both as a learnt behaviour by the fire training instructors (as they were previously operational firefighters), and to provide the recruits with
situations that are as realistic as possible. From field work experience, it is the author’s view that such a work ethos often leads to ‘macho’ attitudes, where firefighters will not exit the scene, either during training or at a real fire, in order not to appear inadequate.

6.5 Clothing

Due to the typically high ambient temperatures that may be experienced during firefighting (see section 6.6), high insulative properties are traditionally provided in firekit (Stirling, 2000). Maximal physical work performance has been reported to be impaired during long-term heat exposure by thick and heavy clothing materials with high insulating properties that have a vapour barrier, which limits body cooling through evaporation (Ilmarinen et al, 1994; Mäkinen et al, 1995; Nunneley, 1989; White & Hodus, 1987). In addition, it has been shown that a poor design and fit of fire-protective clothing or the shoulder harness of SCBA may decrease the mechanical efficiency of moving and breathing, as well as cause discomfort during both submaximal and maximal work (Louhevaara et al, 1984). One study (Louhevaara et al, 1995) which investigated the effects of a multilayer turnout suit designed to fulfil European standard EN 469, used over standardised clothing and with SCBA, found an average decrease in the maximal power output, in terms of maximal working time and

Plate 6.1: Typical firefighting ensemble. This includes: brigade issue socks, underpants, polo shirt, working rig trousers, fire boots, leggings, firetunic (zipped up and buttoned at collar with thumb straps worn), firehood, gloves, Bullard helmet with skirt down, B.A. set and lightweight cylinder.

However, these fire training instructors are not wearing fire hoods, the officer on the right hand side does not have the skirt down on his helmet, and both instructors’ B.A. is not in place.
walking speed, of 25% compared to the control of standard uniform. A typical firefighting ensemble is shown in Plate 6.1.

Similarly, a study investigating firefighting garment style and fabric combinations (Graveling et al, 1999) found a 15% increase in physiological cost at normal room temperatures during treadmill tests, and significant accumulations in body heat in warm, humid environments. They concluded that the levels of physiological strain encountered should be reduced by means such as training in the effects of heat strain and dehydration, and technical means such as additional cooling.

6.6 Physiological Stress Incurred During Firehouse Training
There are several contributing factors to the physiological stress incurred during fire training, as discussed below. Typical ambient temperatures during firefighting range from 38°C to 66°C according to Abeles (1973), but other studies report far more extreme temperatures (Foster & Roberts, 1994; Stirling & Parsons, 1999). The temperature gradient is extremely steep when measured, for example, at one and at two metres, so it is important that the height at which temperature was measured is provided. Fire fighters are taught to remain as low as possible when carrying out structural firefighting. Therefore, standing as opposed to crouching or crawling is likely to cause an increase in heat load. When several firefighting tasks were evaluated, the energy costs were classified as ‘heavy work’ (3.0 VO₂ L.min⁻¹ for simulated rescue work) (Lemon & Hermiston, 1977). The weight and insulating properties of firefighting equipment impose additional stress on firefighters such that the energy cost of moderate work while wearing firefighting clothing and protective equipment is elevated 33% over that required to perform the same work without protective clothing and equipment (Davis & Santa Maria, 1975). Oxygen uptake during stair climbing in protective clothing and breathing apparatus can reach 80% VO₂ max (O'Connell et al, 1986), and it has been reported that firefighting elicits an almost maximal heart rate response for prolonged periods (Barnard & Duncan, 1975; Manning & Grigs, 1983). Firefighters must use SCBA when they operate in highly contaminated atmospheres, but it has been reported that the use of SCBA causes a significant increase in physiological strain during submaximal work, reducing the
working time to exhaustion by 20%, and decreases the maximal work pace by 20% (Raven, et al, 1977; Manning & Grigs, 1983; Louhevaara et al, 1984).

6.7 Hydration

Many of the tasks carried out, equipment used and physiological stresses incurred during firefighter training and instruction are unavoidable. However, being sufficiently hydrated may lessen the effects upon those exposed to extreme heat, particularly fire training instructors, who are exposed for prolonged periods. At present, the only hydration guidance given to firefighters, recruits and instructors is in the form of a Dear Chief Officer Letter (DCOL 8/1997, Item P), which states that brigades should... Section 10(e) ‘ensure firefighters are well-hydrated prior to attending an incident and that body fluid levels are suitably replenished on completion of the task’. The brigades involved in this study have suggested that this guidance is not adequate, and they would need more detailed information on how to remain sufficiently hydrated during fire work, or how to prepare for it and compensate afterwards.

6.7.1 Physiological Effects of Dehydration

Thirst does not provide a good index of body water requirements (Greenleaf, 1992) and numerous investigators report that ad libitum water intake results in incomplete water replacement or ‘voluntary’ dehydration during exercise in the heat (Adolph, 1947; Engell et al, 1987). There are many effects of the process of dehydration, ranging from impaired exercise thermoregulation at about 1% body weight loss to likely collapse at 7% body weight loss (Greenleaf & Harrison, 1986). As dehydration progresses and plasma volume drops, sweating is reduced and thermoregulation becomes progressively more difficult. There is increased heart rate, which can be attributed to a reduced central blood volume that leads to a lower ventricular filling pressure and stroke volume. In order to maintain plasma volume, the body may move fluid from the intra- to the extra-cellular space. In hypohydration, an elevated core temperature is related to a reduction in both sweating and blood flow to the skin (Fortney, 1981a; Nadel et al, 1980) compared to euhydration. Current recommendations for drinking during work in the heat, discussed in more detail in Chapters 7, 8 and 9, are to start drinking at least 2 hours before heat exposure, and to

6.7.2 Cognitive Effects of Dehydration

Cognitive performance is also adversely affected by body water deficits (Adolph, 1947; Ladell, 1955). For many complex industrial tasks, both mental decision making and physiological function are closely related (Sawka, 1992), and the heat stress threshold at which cognitive performance is adversely affected depends upon a complex interplay of factors such as the degree of thermal stress, duration of exposure, acclimatisation and the level of tolerance of individuals (Pepler, 1958). When considering the effects of thermal stress on psychological function, it is generally assumed that performance is dependent upon arousal level. The relationship between heat stress and performance is often defined using the Yerkes-Dodson law, where performance (affected by heat stress) versus arousal produce an inverted U-shape curve (O'Connor, 1993). Although the effects of dehydration upon mental performance are poorly reported in the literature, the influence of heat stress is well reported and may be similar. High levels of heat stress are known to have the following effects upon certain tasks (Nevola, 1998), the high performance of which are vital for fire training instructors: they can cause decrements in the performance of vigilance tasks (observing trainee actions), mental arithmetic (cylinder and exposure times), and spatial reasoning; slow down reaction time and increase time to make decisions (judgements regarding trainee safety); increase the number of errors and inaccuracies apparent within the task; and impair the ability to track signals, both auditory and visual (distress signals). The performance of these tasks is also of great importance to firefighter recruits during training.

Although cognitive performance was not measured in the three studies in this section, hypohydration probably has more profound effects on real life tasks than solely on physiological measures, since usually several tasks are carried out simultaneously. Cumulative errors in such a high risk environment could clearly lead to dangerous, if not life-threatening situations. Control of hydration is therefore of utmost importance for safe working practices.
6.8 Overview

During their work, fire training instructors and firefighter recruits are exposed to extreme atmospheres, carry out ‘heavy’ physical work, and must wear multi-layer protective clothing and SCBA. This combination of factors increases the likelihood of either group suffering from the effects of dehydration and / or heat stress. Considering firefighters are given very little guidance on fluid management at present, a system for monitoring and controlling the hydration state of fire training instructors and firefighter recruits is necessary.

Therefore, the following two chapters (Chapters 7 and 8) determine the extent of dehydration and heat stress in firefighter recruits and fire training instructors during training. Chapter 9 subsequently provides a drinking regime and assesses its effectiveness on fire training instructors, which could be used by all personnel during hot fire training, and as a basis for remaining well hydrated operationally.
Chapter 7
Chapter 7

THE EFFECT OF EXPOSURE TO EXTREME HEAT DURING TRAINING ON THE HYDRATION STATE OF FIREFIGHTER RECRUITS

7.1 Introduction
This chapter aims to determine the extent of hydration problems, in terms of physiological state, with firefighter recruits using the techniques developed in Part II. In addition, if there is a lack of knowledge of hydration issues, provide recruits with advice on remaining well hydrated, using the information gathered in Part I.

This study investigated the effect on hydration states of firefighter recruits from three fire brigades when repeatedly exposed to heat throughout a day’s instruction in a firehouse. Firefighting has long been associated with high physiological demand, and firefighter recruits are exposed to extreme heat on occasions throughout training. During initial training, recruits complete a week’s intensive SCBA instruction, at the end of which they enter the firehouse using the SCBA. Following initial training, all operational firefighters must experience heat and smoke at least four times per year. Throughout ‘hot fire training’ the recruits will often be exposed several times per day in order for them to gain the maximum experience in a situation where there are no civilian lives at risk. Initial training is usually the first time the firefighter recruits will have entered a hot, smoke-filled building, and as well as being inexperienced, it is likely that they will not be acclimatised to the heat.

The firefighter recruits are required to enter the firehouse, which can contain a hot, humid and often polluted atmosphere. They carry out a search of the firehouse, as detailed in Section 6.3.2, in groups of three or four for approximately fifteen to thirty minutes. In order to gain as much experience as possible during hot fire training, the recruits enter the firehouse two or three times per day. The combination of the following factors provides a high level of physiological and psychological stress for the
firefighter recruits: entering a hot, humid, dark, smoke-filled environment; wearing heavy protective clothing and SCBA; being unacclimatised; working at a high activity level; being inexperienced; and working under pressure.

At present, firefighter recruits are given very little advice and no training regarding remaining well hydrated during work in the heat, nor are they told how to prepare for or compensate following heat exposure. Therefore, hydration is a matter for the individual, whether they are informed or not. Since it is well known that thirst does not provide a good index of body water requirements (Greenleaf, 1992) and numerous investigators report that ad libitum water intake results in incomplete water replacement or ‘voluntary’ dehydration during exercise in the heat (Adolph, 1947; Engell, 1987), it was thought necessary to determine the drinking and eating habits, and subsequent hydration states of firefighter recruits before, during and after heat exposure in the firehouse. This was achieved by monitoring recruits’ hydration states during a session of hot fire training. The recruits were also monitored during a session of firefighter training with no heat exposure, throughout which they performed continuous drills and fire exercises on the station ground. The latter was to determine whether there was a hydration problem during drill exercises, as this may contribute to cumulative dehydration throughout recruit training.

7.2 Method

7.2.1 Subjects

Nineteen male firefighter recruits took part in the study on two different occasions. The recruits were from three different brigades, and would have carried out the day of training regardless of the experiment taking place. Subjects completed Human Thermal Environments Laboratory (HTEL) and Loughborough University health screen questionnaire (Appendix I), before written informed consent was obtained. Time was taken prior to the experiment to familiarise the subjects with the experimental procedure and to take measures.

Anthropometric measurements of height, weight and percentage of body fat were taken (according to the equipment and techniques described in Section 2.2.1), and
subject age was also noted. Subjects had a (mean ± SD) height of 178.2 ± 6.1 cm, weight of 80.8 ± 11.9 kg, age of 26.8 ± 4.7 years, and percentage body fat of 14.2 ± 3.3%.

7.2.2 Procedure

The subjects were monitored during a day of firefighter training with no heat exposure, during which they carried out continuous drills and fire exercises on the station ground. Dry and wet bulb temperature were measured on the station ground using a whirling hygrometer (Casella, London, BS 2842/66), and used to calculate relative humidity. The means are shown in Table 7.1. On the second occasion, the subjects were monitored during a day of intermittent training in a firehouse, where exposures lasted approximately 20 minutes each, and subjects undertook either two or three exposures. Subjects rested on the fireground during the time they were not in the firehouse. Temperatures inside the firehouse were measured every minute using shielded air temperature probes situated at 6 different sites throughout the firehouse. The mean and range are shown in Table 7.1. Five of the probes were located throughout the training section of the firehouse, and one was in the crib room where the fire is located. It is possible that the latter temperature probe was influenced by radiation. For this reason, a mean excluding the crib room probe data was calculated separately (Table 7.1). Temperatures were displayed in the control room adjacent to the firehouse throughout the exposure. Dry bulb temperature and relative humidity were measured outside the firehouse where subjects rested, using a whirling hygrometer (Casella, London, BS 2842/66), and these means are shown in Table 7.1.

Table 7.1: Recorded temperatures on the station ground and inside / outside the firehouse

<table>
<thead>
<tr>
<th>Station Ground Training</th>
<th>Firehouse Training</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All probes</td>
</tr>
<tr>
<td>Outside Air temperature (mean ± SD)</td>
<td>19.0 ± 1.8 °C</td>
</tr>
<tr>
<td>Relative humidity (mean ± SD)</td>
<td>56.1 ± 6.2 %</td>
</tr>
<tr>
<td>Inside Air temperature (mean ± SD)</td>
<td>-</td>
</tr>
<tr>
<td>Air temperature (range)</td>
<td>23 - 271.1 °C</td>
</tr>
<tr>
<td></td>
<td>23 - 169.4 °C</td>
</tr>
</tbody>
</table>
The subjects were asked to go about their tasks as normal in order that the experimental results were representative of a usual day of fire training. The hot wear training session was shorter than the exercise drill training session, due to the time taken to prepare the firehouse. The recruits manually calculated their own cylinder time and recorded it on a board prior to entering the firehouse, so that fellow recruits were aware when each recruit should exit the firehouse. They then entered the firehouse in groups of three or four, following a safety line, and proceeded to search the building in the manner described in Section 6.3.2. During the exposures, the firefighter recruits experienced high ambient temperatures, smoke, flooding and casualty rescue.

7.2.3 Measures

The following physiological measures were taken before and after each training session. Mean aural temperature \(T_{\text{ea}}\) was taken upon the first entry and the last exit of the firehouse, and at the beginning and end of the fire training exercises on the station ground. Thermistors were used to measure aural temperature, and were attached to the subject as described in Section 2.2.3. However, data loggers were not taken into the firehouse, or carried during the very active station ground exercises, and therefore subjects plugged each thermistor into a data logger that was available as soon as each session began or ended, in order to record their temperature on each occasion. Subject weight in shorts and the weight of the full fire kit separately (to be used to calculate sweat loss \(S_{\text{wi}}\), sweat rate \(S_{\text{R}}\), sweat trapped in clothing \(S_{\text{wu}}\) and sweat evaporated \(S_{\text{ewap}}\)) were determined using weighing scales (Teraoka Seiko Company Ltd, Tokyo, Japan, Model: DS-410) and the technique described in Section 2.2.1.

Urine samples were taken immediately prior to entering the firehouse for the first time or the start of the station ground drills, and upon exit of the firehouse for the last time or when station ground drills finished (2 samples). Urine was analysed for specific gravity \(U_{\text{sg}}\), colour \(U_{\text{col}}\) and osmolality \(U_{\text{osm}}\), using the equipment and techniques described in Section 4.2.6.
The ASHRAE scale (ASHRAE, 1966) was used to determine overall thermal sensation, where the neutral sensation is given a value of 0 (Fanger, 1970; ISO DIS 7730, 1992) and hot and cold values fall either side. The scale is shown in Figure 2.2. Subjective measures of thirst, nausea and dizziness were also taken using the scales shown in Figures 7.1-7.3. Subjects were asked to record everything they ate and drank, and any exercise they took, from 12 noon the previous day. The subjects' food and drink intake was monitored throughout the day of the experiment. In addition, subjects were asked to contribute comments on an answer sheet on levels of advice and training concerning hydration matters, and personal techniques and experience regarding remaining well-hydrated whilst working in the heat.

<table>
<thead>
<tr>
<th>3</th>
<th>Very thirsty</th>
<th>3</th>
<th>Very nauseous</th>
<th>3</th>
<th>Very dizzy</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Thirsty</td>
<td>2</td>
<td>Nauseous</td>
<td>2</td>
<td>Dizzy</td>
</tr>
<tr>
<td>1</td>
<td>Slightly thirsty</td>
<td>1</td>
<td>Slightly nauseous</td>
<td>1</td>
<td>Slightly dizzy</td>
</tr>
<tr>
<td>0</td>
<td>Not thirsty</td>
<td>0</td>
<td>Not nauseous</td>
<td>0</td>
<td>Not dizzy</td>
</tr>
</tbody>
</table>

*Figure 7.1: Thirstiness scale  Figure 7.2: Nausea scale  Figure 7.3: Dizziness scale*

### 7.2.4 Statistical Analyses

Changes in physiological variables within conditions were analysed for significance using the Student's paired t-test. The Wilcoxon signed-ranks test was used to analyse measures of thermal sensation, thirst, dizziness and nausea. To analyse drinking patterns, 1-sample t-tests and ANOVA's and Tukey's HSD were used. Significance was determined at the $p < .05$ confidence level (where the Bonferroni correction was applied, the significance will be denoted thus: $p^* < .05$), and all terms were expressed as the mean ± SD.
7.3 Results

7.3.1 Aural Temperature

Mean aural temperatures pre- and post- each training session are shown in (Figure 7.4). Temperatures increased significantly during both training sessions ($p^b < .05$). Increase in $T_{au}$ was greater during the heat exposure session than the no heat exposure training session ($p^b < .05$).

Individual aural temperature response (Table 7.2) was as follows: during the heat exposure training session, 5 subjects had an increase in $T_{au}$ of 0.8°C (warning level, BS EN 12515), and a further 11 subjects had an increase in $T_{au}$ of 1.0°C (danger level, BS EN 12515), four of whom exceeded 38°C. Those four subjects went into the firehouse three times; everyone else entered twice. It should be stated that if the starting temperatures were underestimated, perhaps due to lack of time to equilibrate, some of these rises in temperature may not actually be dangerous. No subject reached or exceeded set limits according to international standards during the no heat exposure training session on the station ground.
Table 7.2: Individual aural temperatures pre and post both training sessions

<table>
<thead>
<tr>
<th>Subject Number</th>
<th>No heat exposure</th>
<th>Heat exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>1</td>
<td>36</td>
<td>36.3</td>
</tr>
<tr>
<td>2</td>
<td>36.4</td>
<td>36.5</td>
</tr>
<tr>
<td>3</td>
<td>36.8</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>36.8</td>
<td>36.9</td>
</tr>
<tr>
<td>5</td>
<td>36.6</td>
<td>36.8</td>
</tr>
<tr>
<td>6</td>
<td>36.4</td>
<td>36.9</td>
</tr>
<tr>
<td>7</td>
<td>36.9</td>
<td>37</td>
</tr>
<tr>
<td>8</td>
<td>36.5</td>
<td>36.6</td>
</tr>
<tr>
<td>9</td>
<td>36</td>
<td>36.4</td>
</tr>
<tr>
<td>10</td>
<td>36.2</td>
<td>36.5</td>
</tr>
<tr>
<td>11</td>
<td>36.4</td>
<td>36.6</td>
</tr>
<tr>
<td>12</td>
<td>36.4</td>
<td>36.8</td>
</tr>
<tr>
<td>13</td>
<td>36.2</td>
<td>36.4</td>
</tr>
<tr>
<td>14</td>
<td>36.4</td>
<td>37</td>
</tr>
<tr>
<td>15</td>
<td>36.9</td>
<td>37.3</td>
</tr>
<tr>
<td>16</td>
<td>36.1</td>
<td>36.5</td>
</tr>
<tr>
<td>17</td>
<td>36.4</td>
<td>36.9</td>
</tr>
<tr>
<td>18</td>
<td>36.5</td>
<td>36.7</td>
</tr>
<tr>
<td>19</td>
<td>36.2</td>
<td>36.6</td>
</tr>
</tbody>
</table>

Mean: 36.4 | 36.7  | 36.4  | 37.6
SD: 0.3 | 0.3  | 0.2  | 0.5
Range: 36 - 36.9 | 36.3 - 37.3 | 36 - 37 | 37.1 - 38.5

x: increase in $T_u$ of 0.8°C (warning level, BS EN 12515)
o: $T_u$ reached 38°C
xx: increase in $T_u$ of 1.0°C (danger level, BS EN 12515)

7.3.2 Sweat variables

The mean ($\pm$ SD) total sweat losses were 0.639 ± 0.353 kg and 0.833 ± 0.233 kg throughout the no heat exposure and heat exposure sessions, respectively. These totals comprised of mean sweat evaporated, 0.513 ± 0.364 kg and 0.686 ± 0.251 kg for no heat exposure and heat exposure sessions, respectively, and mean sweat trapped in clothing, 0.126 ± 0.039 kg and 0.147 ± 0.098 kg for no heat exposure and heat exposure sessions, respectively (Figure 7.5).
Individual sweat variable data is shown in Table 7.3. Mean percentage of body weight loss over the no heat exposure training session was 0.79 ± 0.41 %, and 1.04 ± 0.36% over the heat exposure training session. Sweat rates reached means of 183 ± 101 g/hr during no heat exposure, and 476 ± 133 g/hr during heat exposure. Significantly more sweat was lost during heat exposure training than during no heat exposure training (p < .05). Body weight changes (sweat loss) over each of the no heat exposure (p < .05) and heat exposure training sessions (p < .05) were significant. Total sweat loss, body weight loss and fluid intake during each training session are shown in Table 7.4.
### Table 7.3: Individual sweat variables

<table>
<thead>
<tr>
<th>Subject Number</th>
<th>No heat exposure</th>
<th>Heat exposure</th>
<th>Heat exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total sweat loss (kg)</td>
<td>Sweat evaporated (kg)</td>
<td>Sweat trapped in clothing (kg)</td>
</tr>
<tr>
<td>1</td>
<td>0.379</td>
<td>0.180</td>
<td>0.199</td>
</tr>
<tr>
<td>2</td>
<td>0.131</td>
<td>0.036</td>
<td>0.095</td>
</tr>
<tr>
<td>3</td>
<td>0.529</td>
<td>0.333</td>
<td>0.196</td>
</tr>
<tr>
<td>4</td>
<td>0.481</td>
<td>0.392</td>
<td>0.089</td>
</tr>
<tr>
<td>5</td>
<td>0.772</td>
<td>0.714</td>
<td>0.058</td>
</tr>
<tr>
<td>6</td>
<td>0.965</td>
<td>0.829</td>
<td>0.136</td>
</tr>
<tr>
<td>7</td>
<td>0.751</td>
<td>0.629</td>
<td>0.122</td>
</tr>
<tr>
<td>8</td>
<td>0.529</td>
<td>0.443</td>
<td>0.086</td>
</tr>
<tr>
<td>9</td>
<td>1.549</td>
<td>1.452</td>
<td>0.097</td>
</tr>
<tr>
<td>10</td>
<td>0.689</td>
<td>0.590</td>
<td>0.099</td>
</tr>
<tr>
<td>11</td>
<td>0.289</td>
<td>0.143</td>
<td>0.146</td>
</tr>
<tr>
<td>12</td>
<td>0.697</td>
<td>0.654</td>
<td>0.043</td>
</tr>
<tr>
<td>13</td>
<td>0.854</td>
<td>0.829</td>
<td>0.025</td>
</tr>
<tr>
<td>14</td>
<td>0.404</td>
<td>0.306</td>
<td>0.098</td>
</tr>
<tr>
<td>15</td>
<td>0.791</td>
<td>0.697</td>
<td>0.094</td>
</tr>
<tr>
<td>16</td>
<td>0.259</td>
<td>0.112</td>
<td>0.147</td>
</tr>
<tr>
<td>17</td>
<td>1.174</td>
<td>1.038</td>
<td>0.136</td>
</tr>
<tr>
<td>18</td>
<td>0.727</td>
<td>0.630</td>
<td>0.097</td>
</tr>
<tr>
<td>19</td>
<td>0.179</td>
<td>0.030</td>
<td>0.149</td>
</tr>
<tr>
<td>Mean</td>
<td>0.639</td>
<td>0.528</td>
<td>0.111</td>
</tr>
<tr>
<td>SD</td>
<td>0.353</td>
<td>0.368</td>
<td>0.046</td>
</tr>
<tr>
<td>Range</td>
<td>0.131–1.549</td>
<td>0.030–1.452</td>
<td>0.025–0.199</td>
</tr>
</tbody>
</table>

### Table 7.4: Body fluid balance variables during each training session (litres)

<table>
<thead>
<tr>
<th></th>
<th>No heat exposure training</th>
<th>Heat exposure training</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (± SD)</td>
<td>Range</td>
</tr>
<tr>
<td>Total sweat loss over both sessions (S) *</td>
<td>0.639 ± 0.353</td>
<td>0.131 – 1.549</td>
</tr>
<tr>
<td>% BW loss over both sessions</td>
<td>0.79 ± 0.41</td>
<td>0.14 – 1.89</td>
</tr>
<tr>
<td>Total fluid intake (F)</td>
<td>0.725 ± 0.298</td>
<td>0.25 – 1.53</td>
</tr>
<tr>
<td>Fluid balance (F-S)</td>
<td>0.086 ± 0.433</td>
<td>-0.769 – 1.126</td>
</tr>
</tbody>
</table>

* Corrected for urine, faeces, and food and drink intake
7.3.3 Urine measures

Changes in urine variables are shown in Table 7.5. For each variable, a higher value indicates a greater level of hypohydration, and vice versa. For the no heat exposure training session, each of the three urine variables, \( U_{sg} \), \( U_{col} \) and \( U_{osm} \), increases in value from the sample given prior to training to that given post training, reflecting the process of dehydration, but this was not significant. For the heat exposure training session, urine variables show the opposite, and values decrease between samples given prior to and post training. This reflects an improvement in hydration state, but again, this was not significant. Urine specific gravity \( (p^b < .05) \) and urine osmolality \( (p^b < .05) \) values were significantly higher immediately after the no heat exposure training than after the heat exposure training.

Table 7.5: Mean urine measurements taken pre- and post each training session, given with significant results

<table>
<thead>
<tr>
<th></th>
<th>No heat exposure</th>
<th>Heat exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean± SD</td>
<td>Range</td>
</tr>
<tr>
<td>( U_{sg} ) pre</td>
<td>1.015 ± 0.008</td>
<td>1.002 - 1.029</td>
</tr>
<tr>
<td>post</td>
<td>1.019 ± 0.006*</td>
<td>1.010 - 1.027</td>
</tr>
<tr>
<td>( U_{col} ) pre</td>
<td>3 ± 2</td>
<td>1 - 7</td>
</tr>
<tr>
<td>post</td>
<td>4 ± 1</td>
<td>2 - 6</td>
</tr>
<tr>
<td>( U_{osm} ) pre</td>
<td>653 ± 306</td>
<td>136 - 1057</td>
</tr>
<tr>
<td>post</td>
<td>756 ± 236*</td>
<td>282 - 1056</td>
</tr>
</tbody>
</table>

* \( p^b < .05 \) No exposure post vs Exposure post

7.3.4 Drinking patterns

All drink consumed (volume and time consumed) by subjects from 1600 hours the previous day through to 6 hours after each of the training sessions was recorded. Current recommendations advise against drinking caffeine (tea, coffee, coke and chocolate), alcohol, carbonated drinks, oral rehydration solutions (for use with diarrhoea) and carbohydrate-electrolyte beverage concentrations greater than 8% during tasks involving heat exposure (ACSM, 1996; NIOSH, 1986; Nevola, 1998). For this reason, those beverages were categorised separately from “advocated” drinks (water, juice, squash, flavoured beverages with less than 8% carbohydrate, and milk if
desired) in Table 7.6. These recommendations also provide information on how much to drink and how often. The time scales for drinking are given in the key of Table 7.6. The mean actual volume of beverages consumed is compared to the recommended volumes of fluid to drink during these times (ACSM, 1996; Nevola, 1998) in Figure 7.6. With the exception of the ‘2 hours prior to no heat exposure session’ time scale, actual fluid volume consumed never reached the recommended level.

*Figure 7.6:* Mean actual volume of beverages consumed with recommended amounts
Table 7.6: Mean beverage intake before, during and after each training condition (mean ± SD)

<table>
<thead>
<tr>
<th>Time scale</th>
<th>No heat exposure training session</th>
<th>Heat exposure training session</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beverage type (litres)</td>
<td>Beverage type (litres)</td>
</tr>
<tr>
<td></td>
<td>Non-advisable beverages</td>
<td>Non-advisable beverages</td>
</tr>
<tr>
<td></td>
<td>Advocated beverages</td>
<td>Advocated beverages</td>
</tr>
<tr>
<td></td>
<td>Total beverages 20 per minutes</td>
<td>Total beverages 20 per minutes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.763 ± 0.503</td>
<td>0.444 ± 0.312</td>
</tr>
<tr>
<td>R</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1.306 ± 1.004</td>
<td>2.225 ± 1.464</td>
</tr>
<tr>
<td></td>
<td>NR</td>
<td>2.669 ± 1.425</td>
</tr>
<tr>
<td></td>
<td>2.069 ± 0.963</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>0.237 ± 0.101</td>
<td>0.026 ± 0.079</td>
</tr>
<tr>
<td>R</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0.290 ± 0.378</td>
<td>0.442 ± 0.485</td>
</tr>
<tr>
<td></td>
<td>0.527 ± 0.357</td>
<td>0.468 ± 0.494</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>0 ± 0</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>R</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0 ± 0</td>
<td>0 ± 0</td>
</tr>
<tr>
<td></td>
<td>0 ± 0</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>4</td>
<td>0.039 ± 0.094</td>
<td>0.039 ± 0.094</td>
</tr>
<tr>
<td>R</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0.184 ± 0.243</td>
<td>0.379 ± 0.405</td>
</tr>
<tr>
<td></td>
<td>0.224 ± 0.252</td>
<td>0.418 ± 0.398</td>
</tr>
<tr>
<td></td>
<td>0.021 ± 0.024</td>
<td>0.080 ± 0.076</td>
</tr>
<tr>
<td>5</td>
<td>0.396 ± 0.163</td>
<td>0.057 ± 0.141</td>
</tr>
<tr>
<td>R</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0.105 ± 0.244</td>
<td>0.309 ± 0.587</td>
</tr>
<tr>
<td></td>
<td>0.501 ± 0.267</td>
<td>0.366 ± 0.674</td>
</tr>
<tr>
<td></td>
<td>≤ 1.0</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>0.676 ± 0.335</td>
<td>0.597 ± 0.227</td>
</tr>
<tr>
<td>R</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0.452 ± 0.446</td>
<td>0.407 ± 0.588</td>
</tr>
<tr>
<td></td>
<td>1.128 ± 0.504</td>
<td>1.004 ± 0.597</td>
</tr>
<tr>
<td></td>
<td>NR</td>
<td>-</td>
</tr>
</tbody>
</table>

Key:
1 18.25 hours prior to heat exposure
2 2 hours prior to training session
3 15 minutes prior to training session
4 Throughout the training session
5 30 minutes post training session
6 6 hours post training session

R Recommended volume
NR No recommendation available
To determine whether the recruits consumed enough fluid overall, according to the recommendations, the total fluid intake over the day was compared to a hypothetical recommended total (calculated from the recommendations), using a 1-sample t-test. Throughout both days of training (no heat and heat) (including the time prior to training, rest breaks, and 30 minutes post training) the recruits consumed significantly less fluid than is recommended \((p < .05)\) (2.6 and 1.5 litres less, respectively). A further 1-sample t-test was carried out to establish whether the recruits made up for this fluid intake deficit during the six hours following each of the training sessions to equate with the recommended fluid intake for the day of work. The total fluid consumed during the no heat exposure training session and in the six hours following it was still significantly less than the recommended amount \((p < .05)\). However, recruits compensated for low fluid consumption during heat exposure training by drinking enough fluid in the following six hours, as this total was not significantly different from the recommended amount.

To identify whether there was a problem with fluid intake during actual training time (not during breaks), a 1-sample t-test was carried out. The fluid intake during both training sessions was significantly less \((p < .05)\) than the recommended value. To establish if there was a problem with drinking prior to training, a total volume consumed was taken of the two hours prior to each training session and compared to the recommendation using a 1-sample test. During this time, there was significantly less fluid consumed for no heat exposure training \((p < .05)\) and heat exposure training \((p < .05)\) than is recommended.

### 7.3.5 Subjective measures

Mean responses to subjective ratings of overall thermal sensation, thirst, dizziness and nausea have been plotted in Figure 7.7 (the scales used to record subjective responses are shown in the key; however, for representational purposes, the scale in Figure 7.7 only ranges from -1 to 4). There was a significant increase in thermal sensation during heat exposure training \((p^b < .05)\). Mean subjective feelings of thirst showed a significant increase during heat exposure training \((p^b < .05)\). Any changes in feelings of dizziness and nausea were not significant.
Figure 7.7: Mean subjective ratings of overall thermal sensation, thirst, dizziness and nausea pre and post both training sessions (* significantly different from the previous response, $p < .05$)

**Key to use scales:**

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
<th>Rating</th>
<th>Description</th>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+4</td>
<td>Very hot</td>
<td>+3</td>
<td>Hot</td>
<td>+2</td>
<td>Warm</td>
</tr>
<tr>
<td>+1</td>
<td>Slightly warm</td>
<td>0</td>
<td>Neutral</td>
<td>-1</td>
<td>Slightly cool</td>
</tr>
<tr>
<td>-2</td>
<td>Cool</td>
<td>-3</td>
<td>Cold</td>
<td>-4</td>
<td>Very cold</td>
</tr>
<tr>
<td>3</td>
<td>Very thirsty</td>
<td>2</td>
<td>Thirsty</td>
<td>1</td>
<td>Slightly thirsty</td>
</tr>
<tr>
<td>1</td>
<td>Slightly thirsty</td>
<td>0</td>
<td>Not thirsty</td>
<td>0</td>
<td>Not dizzy</td>
</tr>
<tr>
<td>3</td>
<td>Very dizzy</td>
<td>2</td>
<td>Dizzy</td>
<td>1</td>
<td>Slightly dizzy</td>
</tr>
<tr>
<td>1</td>
<td>Slightly nauseous</td>
<td>0</td>
<td>Not nauseous</td>
<td></td>
<td>Not nauseous</td>
</tr>
<tr>
<td>3</td>
<td>Very nauseous</td>
<td>2</td>
<td>Nauseous</td>
<td>1</td>
<td>Slightly nauseous</td>
</tr>
</tbody>
</table>

### 7.3.6 Eating patterns

All food consumed (amounts and time consumed) by subjects was recorded from 1500 hours the previous day through to 6 hours after heat exposure. Since the subjects themselves recorded the food diaries (type and amount), it is difficult to obtain accurate nutritional data. However, the information provides a useful insight into the eating habits of the firefighter recruits. A high proportion of fruit and vegetables in the diet can provide extra body water in addition to drinking (as well as supplying potassium, vitamins, antioxidants and anti-carcinogens). In 1994 a government advisory panel, COMA (Committee on Medical Aspects of Food Policy), (Department of Health, 1994) recommended that in the people living in the UK should eat half as much again of fruit and vegetables as we already eat. It is estimated that the average
consumption is 250-300 grams per person per day, so we should increase our intake by 125-375 grams to 450 grams per day. A project team, set up by the Nutritional Task Force of the Health of the Nation Initiative, recently drew up guidelines on public health messages relating to intake of fruits and vegetables. The advice is to eat 5 portions (a portion is defined as a piece) of fruit and vegetables per day. Between 1500 hours and going to bed on the days prior to training, subjects consumed an average (± SD) of 0.8 ± 0.8 and 0.5 ± 0.6 portions of fruit and vegetables for no heat and heat exposure training, respectively. From rising on each day of training until the end of day, subjects consumed only (mean ± SD) 2.3 ± 1.4 and 1.6 ± 1.2 portions of fruit and vegetables for no heat and heat exposure training, respectively. Therefore, the firefighter recruits did not even consume half the daily recommended amount for an average person in the UK. Since fruit and vegetables could provide the recruits with extra body water and nutrients during training and work in the heat, it is important that they are made aware of the need to consume these amounts.

7.4 Discussion

7.4.1 Aural Temperature

Maximum core temperature values for work in the heat are given in ISO 9886 (1992). When direct measurement of a workforce such as that carried out in this study is not possible, BS EN 12515 (1997) allows predictions to be made regarding maximum working times before critical core temperature increases occur. A draft British Standard is currently in preparation, which takes into account the effect of wearing protective clothing (Hanson, 1998), and can be used in conjunction with BS EN 12515. According to the standards, in the case of both slow and rapid heat storage, the body core temperature limit should be set at an increase of 1°C (danger level, BS EN 12515) or at a temperature of 38°C, whichever comes first (there is also a warning level of an increase of 0.8°C, BS EN 12515). Mean $T_a$ did not exceed the maximum core temperature values of 38°C or a rise of 1°C for work in the heat given in ISO 9886 (1992) with or without heat exposure. Exposure to heat was intermittent throughout the training session at the firehouse, and each exposure only lasted approximately 20 minutes. Therefore, as a group, subjects did not experience excessive heat storage. However, individual $T_a$ response showed that some of the
recruits did exceed these limits: during the heat exposure training session, 5 subjects had an increase in $T_{\text{aw}}$ of 0.8 °C (warning level, BS EN 12515), and a further 11 subjects had an increase in $T_{\text{aw}}$ of 1.0 °C (danger level, BS EN 12515), four of whom exceeded 38 °C. Since this type of training will be the first time many of the recruits have entered a hot, smoke-filled building, these temperature increases are likely to be a response to a combination of inexperience and not being acclimatised. The benefits of heat acclimatisation have been extensively documented (Lind and Bass, 1963; Strydom et al, 1964; Wyndham, 1967; Turk, 1974; Clark and Edholm, 1985; Cheung and McLellan, 1998; Stirling & Parsons, 1998), and it is probable that the firefighter recruits would cope better in the firehouse, both physiologically and psychologically; if they were acclimatised before entering. Although acclimatisation may provide similar physiological stress initially, it would provide the benefits of acclimatisation without working under pressure in a dangerous environment.

7.4.2 Sweat variables
In accordance with BS EN 12515 (1997), total sweat loss limit values are 800g or 1300g for unacclimatised and acclimatised workers respectively. Mean total sweat loss did not exceed these limits during no heat exposure, but just exceeded the unacclimatised limit in the heat exposure session (Figure 7.5). Taking into account drinking, subjects just managed to cover sweat losses during the no heat exposure session (in Table 7.4, body fluid balance (mean ± SD): 0.086 ± 0.433 litres). However, they were in negative fluid balance following the heat exposure session (in Table 7.4, body fluid balance (mean ± SD): -0.536 ± 0.376 litres).

In BS EN 12515, the recommended maximum values account for a maximum water loss of the body of 4-6 % of body mass, depending on whether the subjects are acclimated or not. The subjects did not approach these levels in either experimental condition (mean percentage of body mass lost was 0.79 ± 0.41 % for the no heat exposure session, and 1.04 ± 0.36 % for the afternoon session). However, it is possible that sweating was impaired as a result of the high humidity levels of the microclimate between the skin and protective clothing.
There is a limit applicable concerning the maximum sweat rate: the values of 650 g/hr and 1050 g/hr adopted in BS EN 12515 at the danger threshold for respectively non-acclimatised and acclimatised subjects must be considered as minimal values that can be exceeded by most subjects in good physical condition (ISO 9886). Mean sweat rates for both conditions did not exceed the non-acclimatised threshold, and only two individuals exceeded the non-acclimatised threshold during the heat exposure session. The fact that heat exposure was intermittent and brief is a likely explanation as to why the recruits did not lose excessive amounts of body water, even though they were exposed to strenuous conditions and carried out physically demanding tasks in heavy protective clothing.

7.4.3 Urine measures

Subjects were moderately hypohydrated at the beginning of both sessions. During the training session with no heat exposure, subjects became more hypohydrated, whereas they showed an improvement in hydration state throughout the heat exposure session, neither of which were significant changes. Clearly, this is the opposite of what would have been predicted. In order to examine this, fluids consumed during both training sessions were classed according to which of the four hours of the training session they were consumed in, as shown in Table 7.7. For the no heat exposure session, 63% of fluid was consumed in the last hour of training; it is likely that the small amount of fluid ingested early on in the training session was not enough to cover sweat loss, and that the large amount of fluid taken in during the last hour of the session had not all been emptied from the stomach, so that intestinal absorption had not fully occurred, which is reflected in the urinary indices. However, during the heat exposure training session, more fluid was consumed earlier, and was more likely to have been available at the tissues for sweat and urine production. A possible explanation for such drinking behavior is that the training session on the fireground was almost continuous, and there was little opportunity to drink, but heat exposure was intermittent during training at the firehouse, and recruits were able to consume fluids during rest breaks. Also, upon questioning, subjects seemed to be aware of the need to consume more fluids than usual during heat exposure, but did not think it necessary during training on the fireground. However, since the subjects were in negative fluid balance at the end of
the heat exposure training, it is likely that a urine sample given some hours after the session may have shown a decrement in hydration state.

Table 7.7: Percentage of fluid consumed during each hour of training

<table>
<thead>
<tr>
<th>Hour of training</th>
<th>No heat exposure</th>
<th>Heat exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st hour (0900 - 1000)</td>
<td>10%</td>
<td>32%</td>
</tr>
<tr>
<td>2nd hour (1000 - 1100)</td>
<td>18%</td>
<td>41%</td>
</tr>
<tr>
<td>3rd hour (1100 - 1200)</td>
<td>9%</td>
<td>16%</td>
</tr>
<tr>
<td>4th hour (1200 - 1300)</td>
<td>63%</td>
<td>11%</td>
</tr>
</tbody>
</table>

7.4.4 Drinking patterns

The analyses of drinking patterns sought to determine whether the firefighter recruits consumed enough fluid throughout the day according to recommendations, and if there were particular times during the day where drinking was a problem. Throughout both days of training (no heat and heat exposure training) the recruits consumed significantly less fluid than is recommended ($p < .05$). Although during the six hours following the heat exposure session the recruits made up this deficit in fluid intake, they were not adequately hydrated during their time in the firehouse, which is when their inexperience should be compensated for by proper physiological preparation. The recruits were aware of the need to consume more fluids than usual during heat exposure, and many had brought their own drinks to consume, but they had received no training or guidelines on how to remain well hydrated during work in the heat. In addition, during the two hours prior to both of the training sessions, the recruits consumed significantly less ($p < .05$) fluid than is recommended. It is likely that the recruits were preoccupied with assembling their kits, and also may not have been aware of what was expected of them in the next four hours.

For both of the training sessions, water fountains were available inside an adjacent building; no fluids were provided immediately outside the firehouse or on the training ground, and there was no alternative to water. During the heat exposure training, subjects tended to consume fluids they had brought themselves. In order to encourage fluid intake by recruit firefighters during training, fluids should be readily available, cool, palatable, flavoured (and lightly salted), and may provide a source of energy.
without reducing the rate at which the fluid is absorbed by the body, as with carbohydrate-electrolyte beverages (ACSM, 1996). Training on type and regularity of fluid intake must be provided for the recruits in order to make such a system effective. It is also likely that the recruits may require supervision until regular drinking, before, during and following training, becomes part of their routine.

When a comparison was made between advocated and non-advocated drinks, the recruits consumed significantly more advocated drinks, which is encouraging. The beverages that often contributed to the non-advocated group were canned fizzy drinks that were provided for the recruits. The reasons for avoiding such drinks are detailed below, and since these drinks are a provision of the Fire Service, it would be possible to supply an advocated type of beverage instead. However, drinking the ‘non-advocated’ fluids is generally better than drinking nothing at all (with the exception of alcohol).

What type of beverages should recruits consume, and avoid consuming?
There are a variety of reasons for advising, or advising against, consuming certain beverages in preparation for and during work in the heat. Most obviously, alcohol must not be drunk immediately prior to and during heat exposure because of intoxication and its associated risks in the workplace; however, consuming reasonable amounts of alcohol the night prior to heat exposure means that recruit firefighters are likely to begin the day of training in a state of hypohydration. Having said this, only six out of the nineteen subjects consumed alcohol the night prior to the no heat exposure session, and no subjects did prior to the heat exposure session. It is possible that these low consumption levels may have been due to restrictions in the training regime, as subjects did not seem aware of the effects; it is therefore important that recruits are made aware of the importance of avoiding excessive alcohol intake prior to heat exposure, and to rehydrate adequately if alcohol has been consumed.

Recommendations state that those exposed to heat should avoid consuming caffeine due to its diuretic effects. This is a particularly pertinent issue in this study because of the great ‘tea drinking’ tradition in the fire service. However, it seems that avid caffeine drinkers should not be discouraged from drinking these beverages, as the
The diuretic effect is apparently over-stated and fluid is still in good supply from consuming them (Maughan, 1998).

The main reason for advising against excessive use or reliance on carbonated beverages in order to attain / maintain euhydration is the immediate feeling of satiety that they afford. This is well reported as being detrimental when attempting to consume fluids in adequate volumes with which to effectively reduce the rate of dehydration during heat stress. The higher the relative intensity of the physical activity (expressed in terms of % VO₂ max), the more difficult it is to consume sufficient volumes of fluids. This is because as the additional exercise and heat induced stress raises the work load on the body, sweat rate increases but the appetite for food and drink is concomitantly suppressed.

In addition to consuming water, sports drinks are a convenient and effective way for recruits to meet their fluid and carbohydrate needs throughout repetitive heat exposures, and fire ground training. It has been found that sports drinks can provide the salt and carbohydrate that are necessary to prevent hyponatraemia (Noakes et al, 1985), hypoglycaemia (Coyle et al, 1986) and to improve exercise performance (Mitchell & Voss, 1991) compared to plain water. The possibility of plain water consumption during exercise leading to hyponatraemia is usually the reason put forward for the inclusion of sodium in fluids during exercise. However, all the reported cases of hyponatraemia have been associated with ultra-marathon or prolonged triathlon events (in excess of 8 hours). In all the cases, large volumes (in the region of 6-24 litres) of water or low sodium beverages were consumed (Shirreffs, 1998). A more appropriate reason for the inclusion of sodium in beverages seems to be the increase in palatability that occurs, which is especially important when ad libitum drinking takes place, as in most work place situations. Hubbard et al (1990) state that this is related to the maintenance of thirst and the drive to drink, which is achieved with sodium containing beverages to a greater extent than sodium free beverages. The consumption of carbohydrate during exercise at 60-80 % VO₂ max for between 1 and 3 hours can improve performance (Shirreffs, 1998). A properly formulated sports drink contains 6-7% carbohydrate (ie. 60-70 g/L) (Murray, 1998). This carbohydrate concentration allows the recruits to ingest enough substrate to
improve performance over long or repeated heat exposure, without compromising gastric emptying and intestinal absorption. The flavour and sweetness of sports drinks also helps stimulate voluntary fluid intake, helping assure that fire instructors remain well hydrated.

The pattern of drinking can markedly affect gastric emptying rates of both fluids and carbohydrates (Noakes et al, 1991). Numerous investigations demonstrate that, in comparison to ingesting a single amount, drinking small volumes of dilute (up to 6-7 %) carbohydrate electrolyte solution can maintain a relatively high gastric volume, thereby increasing delivery rates of both carbohydrates and (30-60 g/hr) and fluids (15-20 ml/min) to the small intestine (Mitchell and Voss, 1991; Noakes et al, 1991; Owen et al, 1986; Ryan et al, 1989). Little work has been carried out on the benefits of ingesting carbohydrates for work durations of less than 1 hour, and current guidelines suggest that it is not necessary (ACSM, 1996).

An important issue for the Fire Service is that commercially available sports drinks are generally costly. It is doubtful that the provision of such drinks would be a viable solution throughout the training of firefighter recruits. Based on the demands of each type of training session (heat and no heat) and the physiological measures taken, it is likely that cool, palatable, flavoured and very lightly salted fluids, such as orange squash (which contains a very small amount of salt), in addition to regular meals, would supply firefighter recruits with sufficient fluid and electrolytes. The use of sports drinks as an energy and fluid supply may be necessary during prolonged training sessions, and when operational demands on time and performance are extremely high, such as during extended operational firefighting.

7.4.5 Subjective measures
Mean subjective ratings of thermal sensation for heat exposure mirrored the objective measure of $T_{es}$. However, although many of the subjects exceeded the warning and danger temperature limits of BS EN 12515 (Section 7.3.1), the mean subjective response was slightly above 'warm'. A possible explanation for this discrepancy is that the ISO standards over protect, and the limits given are too low. If this is not the case,
another explanation is that recruits were displaying a macho attitude and preferred not to admit to feeling too hot; this may mean that recruits require monitoring following heat exposure.

The recruits were in negative fluid balance at the end of the heat exposure training session, which was reflected by a significant increase in the sensation of thirst. The dizziness and nausea scales seemed less sensitive to the physiological changes that the subjects experienced, perhaps indicating that they were not sufficiently hypohydrated to report such feelings. This is in keeping with the reported effects of dehydration on humans shown in Table 1.2, where dizziness is not expected to occur until a loss of 8% of body weight has taken place. Feelings of nausea were not reported at all in Greenleaf’s (Table 2.1) summary, and there were few reports of feelings of nausea in this study also.

7.4.6 Eating patterns
Since the recruits eat on the station throughout the training period, it would be logical to pass on nutritional information to personnel such as the kitchen staff, so that recruits are provided with a balanced diet, and one that complements work in the heat. It would also be pertinent to advise the recruits on dietary matters in order that they could observe such practises at home and at their own station once their training has finished and they have become firefighters.

7.4.7 Knowledge of hydration issues
Gathering this information did not take the form of a structured interview; instead, subjects noted down levels of advice and training concerning hydration matters, and personal techniques and experience regarding remaining well-hydrated whilst working in the heat. No subject had received any official training or advice regarding hydration matters. Most individuals were aware of the need to drink following heat exposure, but few were informed on the need to intake sufficient fluids prior to and during heat exposure. Some subjects did note that it was difficult to consume fluids ad libitum, particularly during the training session on the fire ground with no heat exposure, because they were expected to continue with set tasks, and as such, were not ‘their
own men’. It is therefore important that regular breaks are provided during training to allow and encourage adequate fluid intake by the recruits.

### 7.1 Conclusions

- Mean $T_{au}$ response showed that the recruits did not experience excessive rises in $T_{au}$ during either training session. However, individual $T_{au}$ response during the heat exposure session showed that some recruits exceeded the warning and danger limits of BS EN 12515 (1997).

- Urinary measures of hydration did not show significant changes throughout either of the training sessions.

- Recruits consumed enough fluids during the no heat training session to remain in fluid balance, but were in negative fluid balance following the heat exposure training session. Therefore, encouragement may be necessary to continue fluid replacement once a training session has ceased.

- Throughout both days of training, recruits consumed less fluid than is recommended, both prior to and during the session. Recruits made up this deficit in the six hours following heat exposure, but did not in the six hours following the no heat exposure training.

- Recruit firefighters need to be made aware of the need to consume fluids prior to, regularly throughout, and following physical work. It is clear that training and advice is necessary regarding type, volume and timing of rehydration fluids.

- The firefighter recruits did not experience a significant dehydration problem, but the provision of accessible, cool, palatable, flavoured and lightly salted fluids is necessary to encourage effective rehydration regimes in firefighter recruits.
Chapter 8
Chapter 8

THE EFFECT OF PROLONGED HEAT EXPOSURE ON THE HYDRATION STATE OF FIREFIGHTER INSTRUCTORS

8.1 Introduction

Firefighter recruits do not suffer significant dehydration problems during training, as shown in Chapter 7. This is because even with only adequate drinking they are not exposed to the heat for long periods of time during hot fire training, and this type of training only constitutes a fraction of the recruitment course. Fire training instructors, however, can be exposed to extreme heat on a daily basis, often several times per day. The fire training instructors escort and instruct recruits in hot, humid and often polluted atmospheres, incurring great levels of physiological stress, as discussed in Chapter 6. This study investigated the effect on hydration states of fire training instructors when repeatedly exposed to heat throughout a day's instruction in a firehouse. It aimed to determine the extent of physiological effects of dehydration, and, as with the recruits, provide advice on remaining well-hydrated if there was a problem.

Many of the tasks carried out, equipment used and physiological stresses incurred during firefighting and instruction are unavoidable. However, being sufficiently hydrated may lessen the effects, both psychological and physiological, upon those exposed to extreme heat. This is particularly pertinent to fire training instructors, who are exposed to heat for prolonged periods themselves and are responsible for the behaviour and safety of the inexperienced recruits in the firehouse. Prevention of dehydration is therefore of utmost importance for safe working practices.

Much work has been carried out on the tasks involved in firefighting, breathing apparatus, and the fitness levels of recruits and fire training instructors (see Chapter 6); however, there has been little investigation into the day to day physiological state, particularly hydration state, of fire training instructors. Three brigades (Leicestershire, Staffordshire and West Midlands) expressed concern that their fire training instructors...
were not adequately hydrated during work in firehouses. It is hypothesised that this may be due to a combination of several factors: the unavailability of palatable fluids outside the firehouse; ignorance of the need to drink sufficient amounts of fluid before, during and after heat exposure; the food provided on fire stations has a low water content; ignorance of the need to consume more fluids than usual if alcohol has been consumed or heavy exercise has been carried out prior to heat exposure; and, anecdotally, that fire training instructors avoid drinking in order that they will have to remove their kit fewer times to urinate. In order to ascertain whether current working practices are optimal and to make recommendations, this study sought to determine the drinking and eating habits, and subsequent hydration states of fire training instructors before, during and after heat exposure whilst training recruits in the firehouse.

8.2 Method

8.2.1 Subjects

Eight male fire training instructors were monitored during a normal day of recruit training in a firehouse on a fire station. The instructors were from three different brigades, and would have carried out the day’s training regardless of the experiment taking place. Subjects completed Human Thermal Environments Laboratory (HTEL) and Loughborough University health screen questionnaire (Appendix I), before written informed consent was obtained. Time was taken prior to the experiment to familiarise the subjects with the experimental procedure and to take measures.

Anthropometric measurements of height, weight and percentage of body fat were taken (according to the equipment and techniques described in Section 2.2.1), and subject age was also noted. Subjects had a (mean ± SD) height of 182.5 ± 5.1 cm, weight of 84.8 ± 13.3 kg, age of 39.4 ± 3.8 years, and percentage body fat of 19.2 ± 5.3%.

8.2.2 Procedure

The subjects were exposed to the heat during two training sessions throughout the day and had a break of approximately 50 minutes in between heat exposures. Temperatures inside the firehouse were measured every minute using air temperature
probes situated at 6 different sites throughout the firehouse. The means are shown in Table 8.1. Five of the probes were located throughout the training section of the firehouse, and one was in the crib room where the fire is located. It is possible that the latter temperature probe was influenced by radiation. For this reason, a mean excluding the data from this probe was also calculated (Table 8.1). Temperatures were displayed in the control room adjacent to the firehouse throughout the exposure. Dry bulb and wet temperature were measured outside the firehouse where subjects rested, with a whirling hygrometer (Casella, London, BS 2842/66), and were used to calculate relative humidity (rh). Air temperature and rh averaged ($\pm$ SD) 18.8 $\pm$ 1.4 $^\circ$C and 68.0 $\pm$ 6.7 % for the morning session and 20.1 $\pm$ 0.7 $^\circ$C and 57.3 $\pm$ 2.0 % for the afternoon session, respectively.

<table>
<thead>
<tr>
<th>Table 8.1: Recorded temperatures inside the firehouse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>All probes</td>
</tr>
<tr>
<td>Air temperature (mean $\pm$ SD)</td>
</tr>
<tr>
<td>Air temperature (range)</td>
</tr>
</tbody>
</table>

The subjects were asked to go about their tasks as normal in order that the experimental results were representative of a usual day of fire training. The tasks carried out by six of the fire training instructors involved: dragging a range of dummies (30 - 70 kg) to set locations for recruits to find; escorting and observing recruits in the firehouse; physically moving or pulling down recruits who placed themselves in dangerous positions; and generally overseeing the safety of the recruits in the firehouse. The remaining two instructors were acting as 'stokers', which involves lighting the fire and keeping it at a high enough temperature to simulate a real fire for the recruits to practice in, as well as carrying out the tasks above. These two personnel were exposed to extremely high air temperatures (73.6 - 205.0$^\circ$C) throughout the sessions.
8.2.3 Measures
The following physiological measures were taken before and after each heat exposure. Mean aural temperature ($T_{au}$) was taken on entry and exit from the firehouse. Thermistors were used to measure aural temperature, and were attached to the subject as described in Section 2.2.3. Thermistors were plugged into the data loggers outside the firehouse, as described in Section 7.2.3. Subject sweat parameters were determined using the technique described in Section 2.2.1.

Urine samples were taken immediately prior to entering the firehouse, and upon exit from the firehouse for both training sessions (4 samples). Urine was analysed for specific gravity ($U_{sg}$), colour ($U_{col}$) and osmolality ($U_{osm}$), using the equipment and techniques described in Section 4.2.6.

Subjective sensations were recorded as shown in Section 7.2.3. Subjects were asked to record everything they ate and drank, and any exercise they took, from 12 noon the previous day. The subjects' food and drink intake was monitored throughout the day of the experiment. In addition, subjects were asked to contribute comments on an answer sheet on levels of advice and training concerning hydration matters, and personal techniques and experience regarding remaining well-hydrated whilst working in the heat.

8.2.4 Statistical Analyses
Data was analysed in the same manner as described in Section 7.2.4.

8.3 Results
8.3.1 Aural Temperature
For the morning session of training, mean aural temperature was 36.5 °C before entering the firehouse and 38.2 °C upon exiting. For the afternoon session of training, mean aural temperature was 36.5 °C before entering the firehouse and 37.4 °C upon exiting (Figure 8.1). Increase in mean aural temperature over the morning session was significant ($p^b < .05$), as was the increase over the entire day of training ($p^b < .05$). Mean temperature significantly decreased ($p^b < .05$) during the rest break between
sessions. Data for individual aural temperature response upon entry and exit to the firehouse is given in Table 8.2.

![Graph showing aural temperatures](image)

**Figure 8.1:** Mean aural temperatures upon entry and exit of the firehouse

<table>
<thead>
<tr>
<th>Time of day</th>
<th>1030</th>
<th>1230</th>
<th>1325</th>
<th>1450</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB</td>
<td>37.1</td>
<td>37.8</td>
<td>37.3</td>
<td>37.6</td>
</tr>
<tr>
<td>JS</td>
<td>36.4</td>
<td>38.2 xx</td>
<td>35.2</td>
<td>37.2 xx</td>
</tr>
<tr>
<td>CS</td>
<td>35.9</td>
<td>37.8 xx</td>
<td>36.2</td>
<td>37.2 xx</td>
</tr>
<tr>
<td>JN</td>
<td>37.2</td>
<td>37.7</td>
<td>37.5</td>
<td>37.1</td>
</tr>
<tr>
<td>MW</td>
<td>36.4</td>
<td>38.2 xx</td>
<td>36.8</td>
<td>37.6 x</td>
</tr>
<tr>
<td>MC</td>
<td>36</td>
<td>38.8 xx</td>
<td>36</td>
<td>38.4 xx</td>
</tr>
<tr>
<td>PB</td>
<td>36.7</td>
<td>38.3 xx</td>
<td>37.2</td>
<td>36.9</td>
</tr>
<tr>
<td>BB</td>
<td>36</td>
<td>39</td>
<td>36</td>
<td>37.6 xx</td>
</tr>
<tr>
<td>Mean</td>
<td>36.5</td>
<td>38.2</td>
<td>36.5</td>
<td>37.5</td>
</tr>
<tr>
<td>SD</td>
<td>0.5</td>
<td>0.47</td>
<td>0.8</td>
<td>0.47</td>
</tr>
<tr>
<td>Range</td>
<td>35.9-37.2</td>
<td>37.7-39</td>
<td>35.2-37.5</td>
<td>36.9-38.4</td>
</tr>
</tbody>
</table>

x: increase in $T_m$ of 0.8°C (warning level, BS EN 12515)  
o: $T_m$ reached 38°C  
xx: increase in $T_m$ of 1.0°C (danger level, BS EN 12515)
8.3.2 Sweat variables

The mean (± SD) total sweat losses were 1.34 ± 0.93 kg and 0.87 ± 0.3 kg throughout the morning and afternoon sessions, respectively. These totals comprised of mean sweat evaporated, 0.71 ± 0.76 kg and 0.56 ± 0.31 kg for morning and afternoon sessions, respectively, and mean sweat trapped in clothing, 0.63 ± 0.3 kg and 0.31 ± 0.19 kg for morning and afternoon sessions, respectively (Figure 8.2).

![Figure 8.2: Mean total sweat loss, sweat evaporated and sweat trapped in clothing over morning and afternoon sessions](image)

Mean percentage of body weight loss over the morning was 1.57 ± 0.89 %, and 1.04 ± 0.36% over the afternoon. Sweat rates reached means of 672 ± 464 g/hr in the morning, and 611 ± 210 g/hr in the afternoon. Body weight changes (sweat loss) over each of the morning ($p^b < .05$) and afternoon ($p^b < .05$) sessions were significant, as was the change over the entire day ($p^b < .05$). Individual and mean data for total sweat loss, body weight loss and fluid intake are shown in Table 8.3.
Table 8.3: Body fluid balance variables over the entire day of testing (litres)

<table>
<thead>
<tr>
<th></th>
<th>Total sweat loss over both sessions (S)*</th>
<th>% BW loss over both sessions</th>
<th>Total fluid intake (F)</th>
<th>Fluid balance (F-S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB</td>
<td>1.25</td>
<td>1.40</td>
<td>1.40</td>
<td>0.15</td>
</tr>
<tr>
<td>JS</td>
<td>1.80</td>
<td>1.84</td>
<td>2.48</td>
<td>0.68</td>
</tr>
<tr>
<td>CS</td>
<td>4.84</td>
<td>4.50</td>
<td>2.83</td>
<td>-2.01</td>
</tr>
<tr>
<td>JN</td>
<td>1.15</td>
<td>1.50</td>
<td>1.98</td>
<td>0.83</td>
</tr>
<tr>
<td>MW</td>
<td>1.85</td>
<td>2.52</td>
<td>2.22</td>
<td>0.37</td>
</tr>
<tr>
<td>MC</td>
<td>2.30</td>
<td>2.89</td>
<td>1.98</td>
<td>-0.32</td>
</tr>
<tr>
<td>PB</td>
<td>1.70</td>
<td>1.95</td>
<td>1.78</td>
<td>0.08</td>
</tr>
<tr>
<td>BB</td>
<td>2.80</td>
<td>4.16</td>
<td>1.23</td>
<td>-1.57</td>
</tr>
<tr>
<td>Mean</td>
<td>2.21</td>
<td>2.60</td>
<td>1.99</td>
<td>-0.22</td>
</tr>
<tr>
<td>SD</td>
<td>1.19</td>
<td>1.18</td>
<td>0.53</td>
<td>1.04</td>
</tr>
<tr>
<td>Range</td>
<td>1.15 - 4.84</td>
<td>1.4 - 4.5</td>
<td>1.23 - 2.83</td>
<td>-2.01 - 0.83</td>
</tr>
</tbody>
</table>

* Corrected for urine, faeces, and food and drink intake

8.3.3 Urine measures

Each of the three urine variables, specific gravity (U_{sg}), colour (U_{col}) and osmolality (U_{osm}), produced a similar pattern over the time course of the day (Figure 8.3).

![Figure 8.3: Urine measures (mean values) over the time course of the day: specific gravity, colour and osmolality (colour chart ranges from 1-8, and 1.0 should precede all specific gravity values, eg. 1.017)'](image-url)
Urine variable means (± SD) and ranges are shown in Table 8.4. Variable values decreased between samples given before and after the morning session, which reflects an improvement in hydration state. Subjects gave another sample just prior to beginning the afternoon session (after the rest break); values increased from the post morning session samples, reflecting the process of dehydration. The further increase in variable values of the samples given following the afternoon session represents a greater level of hypohydration.

Table 8.4: Mean urine measurements taken pre and post morning and afternoon sessions in the firehouse, given with significant results (see text for values)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Time</th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urine specific gravity (U_s)</td>
<td>Morning - pre</td>
<td>1.018 ± 0.007 *ΨΨ</td>
<td>1.005 - 1.026</td>
</tr>
<tr>
<td></td>
<td>Morning - post</td>
<td>1.013 ± 0.008 *Ψ</td>
<td>1.005 - 1.024</td>
</tr>
<tr>
<td></td>
<td>Afternoon - pre</td>
<td>1.017 ± 0.008 Ψ</td>
<td>1.006 - 1.027</td>
</tr>
<tr>
<td></td>
<td>Afternoon - post</td>
<td>1.022 ± 0.007 *ΨΨ</td>
<td>1.010 - 1.028</td>
</tr>
<tr>
<td>Urine colour (Ucol)</td>
<td>Morning - pre</td>
<td>4 ± 2 *ΨΨ</td>
<td>2 - 6</td>
</tr>
<tr>
<td></td>
<td>Morning - post</td>
<td>3 ± 1 *Ψ</td>
<td>2 - 6</td>
</tr>
<tr>
<td></td>
<td>Afternoon - pre</td>
<td>4 ± 2 *ΨΨ</td>
<td>2 - 7</td>
</tr>
<tr>
<td></td>
<td>Afternoon - post</td>
<td>6 ± 2</td>
<td>3 - 7</td>
</tr>
<tr>
<td>Urine osmolality (U_om)</td>
<td>Morning - pre</td>
<td>679 ± 277 ΨΨ</td>
<td>194 - 1022</td>
</tr>
<tr>
<td></td>
<td>Morning - post</td>
<td>556 ± 284</td>
<td>301 - 971</td>
</tr>
<tr>
<td>(mOsmol / kg H2O)</td>
<td>Afternoon - pre</td>
<td>673 ± 268 *ΨΨ</td>
<td>301 - 1007</td>
</tr>
<tr>
<td></td>
<td>Afternoon - post</td>
<td>862 ± 204</td>
<td>542 - 1133</td>
</tr>
</tbody>
</table>

Significant changes
* Same session, pre vs post
(ΨΨΨ) Morning post vs afternoon pre
(ΨΨΨ) Morning pre vs afternoon post

8.3.4 Drinking patterns

All drink consumed (volumes and time consumed) by subjects from 12 noon the previous day through to 6 hours after heat exposure was recorded. This was compared with current recommendations on what and when to drink during work in the heat (ACSM, 1996; ACGIH, 1996; Nevola, 1998; NIOSH, 1986), as in Section 7.3.4.
To determine whether the instructors consumed enough fluid overall, according to the recommendations, the total fluid intake over the day was compared to a hypothetical recommended total (calculated from the recommendations), using a 1-sample t-test. For this day of training (including the time prior to training, rest breaks, and 30 minutes post training), the recommendations state that the instructors should have consumed 4.65 litres of fluid; however, they consumed (mean ± SD) 1.83 ± 0.78 litres, which is significantly less fluid than is recommended (p < .05). A further 1-sample t-test was carried out to establish whether the instructors consumed enough extra fluid in the six hours following heat exposure to equate with the recommended fluid intake for the day of work in the heat. The instructors total fluid intake throughout the day and in the six hours following heat exposure was still significantly less than recommended (p < .05).
To identify whether there was a problem with fluid intake during heat exposure (not including breaks), a 1-sample t-test was carried out on the mean values of the first and second heat exposures. The average fluid intake over both heat exposures was significantly less ($p < .05$) than the recommended value. To establish if there was a problem with drinking during rest, a mean was taken of the 15 minutes prior to each heat exposure and compared to the recommendation using a 1-sample test (the 2 hours prior to heat exposure could not be analysed, as the second set was confounded by consisting of heat exposure 1 and rest data between the two heat exposures). During rest there was significantly less fluid consumed than is recommended ($p < .05$). Since all the instructors knew they would be carrying out work in the firehouse, a 1-sample t-test was used to compare their drinking patterns in the 2 hours prior to the first heat exposure to the recommendations. The volume of fluid consumed was not significantly different from the recommended amount. In order to test if the instructors consumed more of a certain type of drink and if time throughout the day of testing had an effect, a balanced ANOVA was carried out, separating drinks into 'advocated' and non-advocated'. The main effects were significant ($p < .05$), so that the instructors...
drank significantly more advocated drinks, and time scale throughout the day had an effect.

### 8.3.5 Subjective measures

Mean responses to subjective ratings of overall thermal sensation, thirst, dizziness and nausea have been plotted in Figure 8.5 (the scales are shown in the key; however, for representational purposes, the scale only ranges from 0 to 4). For thermal sensation, the changes over the morning session ($p^b < .05$) and over the rest break ($p^b < .05$) were significant, as was the change in thermal sensation over the entire day ($p^b < .05$). Mean subjective feelings of thirst changed significantly over the entire day ($p^b < .05$). Any changes in feelings of dizziness and nausea were not significant.

![Figure 8.5: Mean subjective ratings of overall thermal sensation, thirst, dizziness and nausea over the time course of the day (* significantly different from the previous response, † significant change from the first response to the last response of the day. See text for significance values)](image)

**Key to use scales:**

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+4</td>
<td>Very hot</td>
</tr>
<tr>
<td>+3</td>
<td>Hot</td>
</tr>
<tr>
<td>+2</td>
<td>Warm</td>
</tr>
<tr>
<td>+1</td>
<td>Slightly warm</td>
</tr>
<tr>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>-1</td>
<td>Slightly cool</td>
</tr>
<tr>
<td>-2</td>
<td>Cool</td>
</tr>
<tr>
<td>-3</td>
<td>Cold</td>
</tr>
<tr>
<td>-4</td>
<td>Very cold</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Very thirsty</td>
</tr>
<tr>
<td>2</td>
<td>Thirsty</td>
</tr>
<tr>
<td>1</td>
<td>Slightly thirsty</td>
</tr>
<tr>
<td>0</td>
<td>Not thirsty</td>
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</tbody>
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<table>
<thead>
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<th>Rating</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
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<td>Very dizzy</td>
</tr>
<tr>
<td>2</td>
<td>Dizzy</td>
</tr>
<tr>
<td>1</td>
<td>Slightly dizzy</td>
</tr>
<tr>
<td>0</td>
<td>Not dizzy</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Very nauseous</td>
</tr>
<tr>
<td>2</td>
<td>Nauseous</td>
</tr>
<tr>
<td>1</td>
<td>Slightly nauseous</td>
</tr>
<tr>
<td>0</td>
<td>Not nauseous</td>
</tr>
</tbody>
</table>
8.3.6 Eating patterns

All food consumed (amounts and time consumed) by subjects over the period from 12 noon the previous day through to 6 hours after heat exposure was recorded. Since the subjects themselves recorded the food diaries (type and amount), it is difficult to obtain accurate nutritional data. However, the information provides a useful insight into the eating habits of the fire training instructors. The current recommendations for fruit and vegetables in a UK diet are discussed in Section 7.3.6. The advice is to eat 5 portions of fruit and vegetables per day. Between 12 noon and going to bed the day prior to heat exposure, subjects consumed an average (± SD) of 2 ± 1.4 portions of fruit and vegetables. From rising on the day of heat exposure until the end of day, subjects consumed only (mean ± SD) 1.9 ± 1.3 portions of fruit and vegetables. Therefore, the fire instructors did not even consume half the daily recommended amount for an average person in the UK. Since fruit and vegetables could provide the instructors with extra body water and nutrients while working in the heat, it is important that they are made aware of the need to consume these amounts.

8.3.7 Exercise patterns

Subjects were asked to detail the type and length of any physical exercise they undertook from 12 noon the day prior to heat exposure until the heat exposure. Results showed that any exercise carried out took place the day prior. Using tables of estimates of metabolic rate (Parsons, 1993b), and data supplied with exercise equipment, a mean (± SD) metabolic rate of 91 ± 132 W/m² was estimated for exercise carried out by all 8 subjects in this period. Using BS EN 12515 (1997), the estimated sweat loss in order to maintain core temperature was (mean ± SD) 314 ± 466 g/h. Upon closer inspection of the data, it can be seen that these means are only made up of three subjects' data, as five did not exercise at all. For these three subjects, estimated mean (± SD) sweat loss was 836 ± 325 g/h (BS EN 12515, 1997), which was 1.178 ± 0.621 kg of sweat loss for those particular activities. For the same 3 subjects, mean (± SD) fluid intake in the 22.5 hours preceding heat exposure was 3.65 ± 2.16 litres (1.89 ± 0.591 litres of which was from the 'advocated' drinks category). Therefore, fluid lost in exercise was sufficiently replaced.
8.4 Discussion

8.4.1 Aural Temperature

According to the International Standards, in the case of both slow and rapid heat storage, the body core temperature limit should be set at an increase of 1°C (danger level, BS EN 12515) or at a temperature of 38°C, whichever comes first (there is also a warning level of an increase of 0.8°C, BS EN 12515). Although the mean aural temperature after the morning session only exceeded the 38°C limit by 0.2 °C, and during the afternoon session, the limit was not exceeded (Figure 8.1), a closer inspection of individual data (Table 8.2) reveals more information: during the morning session, five subjects exceeded the 38°C limit (two also reached or exceeded 38.8 °C), and six subjects had an increase of at least 1.0 °C (danger level); during the afternoon session, one subject exceeded the 38°C limit, four subjects had an increase of at least 1.0 °C (danger level), and one subject had an increase of 0.8°C (warning level). The afternoon session was shorter and slightly cooler (Table 8.1), which was reflected in $T_{au}$. However, had the sessions been equal in duration and temperature, which is feasible, there may have been a cumulative effect throughout the day, leading to heat stress casualties. The fall in $T_{au}$ of subjects JN and PB during the afternoon session was due to them leaving the firehouse in order to supervise a situation with the trainees outside the firehouse; as a result, their temperatures could not be recorded as soon as they exited the firehouse.

8.4.2 Sweat variables

In accordance with BS EN 12515, total sweat loss limit values are 800g or 1300g for unacclimatised and acclimatised workers respectively. Mean total sweat loss exceeded both limits during the morning session (one subject (CS) exceeded the acclimatised limit by almost three times), and exceeded the unacclimatised limit for the afternoon session (Figure 8.2). In BS EN 12515, the recommended maximum values account for a maximum water loss of the body of 4-6 % of body mass, depending on whether the subjects are acclimated or not. The subjects in this experiment did not approach these levels during individual heat exposures (mean percentage of body mass lost was 1.57 ± 0.89 % for the morning session, and 1.04 ± 0.36 % for the afternoon session), but the total percentage of body weight lost over the entire day of training was of a
more consequential level (Table 8.3). It is also possible that sweating was impaired as a result of the high humidity levels of the micro-climate between the skin and protective clothing.

Upon inspection of individual data, two subjects were in the 4-6% body weight loss range (the two stokers). Considering fire training instructors are often exposed to heat more than twice per day, these figures are potentially dangerous. Although BS EN 12515 states that levels of up to 4-6% body weight loss are acceptable, if we refer to Table 1.2, which details effects on humans at different levels of dehydration, symptoms such as impatience, apathy, difficulty in concentrating, impairment in exercise temperature regulation and increased heart rate are likely to occur before these recommended levels are reached or surpassed. Experiencing such symptoms is clearly unacceptable in the job of a fire training instructor.

There is a limit applicable concerning the maximum sweat rate: the values of 650 g/hr and 1050 g/hr adopted in BS EN 12515 at the danger threshold for respectively non-acclimatised and acclimatised subjects must be considered as minimal values that can be exceeded by most subjects in good physical condition (ISO 9886). Sweat rates in this experiment exceeded the non-acclimatised threshold during the morning session, 672 ± 464 g/hr, but exceeded neither during the afternoon session, 611 ± 210 g/hr. However, these standards assume normal rehydration, and in this experimental scenario, and indeed in the job of a fire training instructor at present, normal rehydration procedures are not possible. In addition, there is clear evidence that the amount of sweat production depends on the state of hydration (Leithead & Lind, 1964; Henschel, 1971; Greenleaf, 1985; NIOSH, 1986), so that progressive hypohydration results in a lower sweat production and a corresponding increase in body temperature. Although sweat rate during each heat exposure was not monitored, there was a recorded increase in body temperatures of the fire instructors (Figure 8.1 and Table 8.2).
Plate 8.1: This subject's undergarments were soaked, as the sweat produced had not been able to evaporate through the firekit. This loss of vital body water contributes little to heat transfer away from the body.

Regarding clothing properties, the amount of sweat evaporated through the fire kit was similar during both sessions (no significant difference), but although not significant, there was a trend of the amount of sweat trapped in clothing being greater in the morning than the afternoon ($p = .058$) (Figure 8.2). It is likely that no more sweat evaporated throughout the morning session (when more sweat was produced) than the afternoon session because the firekit became wet through sweat absorption, and sweat could only be transported by capillary action to the clothing surface, rather than by vapour transfer. Therefore, sweating was probably more efficient in the afternoon, so that the difference between sweat rate and evaporation rate was less in the afternoon than the morning. Plate 8.1 shows one of the subjects with his undergarments soaked with sweat; since this sweat could not evaporate through the fire kit, heat loss was not promoted.

8.4.3 Urine measures

Since variable values decreased over the morning session (Figure 8.3), reflecting an improvement in hydration state, but subjects' sweat loss was greater than fluid intake, there is clearly an irregularity. Furthermore, variable values increased over the rest break (a deterioration in hydration state), yet fluid intake exceeded sweat loss. A possible explanation for this is that the sweat produced during the heat exposure would have depleted the plasma volume, since plasma provides the precursor fluid to sweat (Sawka, 1996). Therefore, in order to allow the body to maintain physical work in the
heat, fluid may have moved from the intracellular to the extracellular space in order to restore plasma volume. When the subjects ceased work in the heat, causing less strain on the circulatory, thermoregulatory and metabolic systems, the displaced fluid would have returned to the intracellular space. This could explain the apparent improvement in hydration state during the heat exposure: fluid shifts within the body provided extra water to support the conflicting systems until activity ceased.

It is possible that too much body water had been lost as sweat throughout the day for body fluid shifts to compensate during the afternoon heat exposure; this process could explain the deterioration in hydration state over the exposure (Figure 8.3). Therefore, if fluid shifts did take place, a sample given later in the afternoon or evening may have demonstrated variable values that had become even more hypohydrated as fluid shifted back to the intracellular space following the cessation of activity.

This therefore creates an issue with the usage of such hydration state indicators (also discussed in Chapter 7); if the fluid shifts did occur in the processes detailed above, then it is important that hydration indices are not underestimated and that monitoring continues for several hours after heat exposure to allow the redistribution of fluids to take place. In addition, fluids taken in prior to the morning session may have only become available in the body tissues towards the end of the heat exposure; likewise, fluids taken in during the rest break (55 minutes duration) had not become available by the start of the afternoon heat exposure. This emphasises the need to drink several hours prior to heat exposure, and throughout it (discussed in detail in 8.4.4 Drinking patterns). This may mean that urine measures are more useful for monitoring hydration state over longer periods, such as several days, rather than just the day of heat exposure.

8.4.4 Drinking patterns

The analyses of drinking patterns sought to determine whether the fire instructors consumed enough fluid throughout the day according to recommendations, and if there were particular times during the day where drinking was a problem.
Throughout the day of testing, the instructors consumed significantly less fluid than is recommended \((p < .05)\), and they did not consume enough fluid in the following 6 hours to make up this difference. This may have implications if the instructors were carrying out hot fire training the next day.

The average fluid intake during both heat exposures was significantly less than the recommended amount \((p < .05)\). This may have been due to a lack of awareness of the need to drink, or because removing the facemask of the BA in order to drink was too time consuming.

During the 15 minutes prior to both heat exposures, the instructors again consumed significantly less than the recommended amount \((p < .05)\), even though they had not yet donned their full fire kit and BA. It is likely that the instructors did not drink in this time period because they were preoccupied with assembling their fire kits, preparing the firehouse for use, and organising the recruits for the heat exposure. Therefore, instructors must be alerted to the fact that they need to prepare themselves sufficiently, i.e. consume ample amounts of fluid, prior to a heat exposure if they are to carry out their tasks optimally. Since all the instructors knew that they would be carrying out work in the firehouse that day, a comparison was made with the recommendation and the amount consumed in the 2 hours prior to the first heat exposure. This amount was not significantly different, so it would appear that the instructors were better able to prepare for work in the heat when they had fewer things to concentrate on. However, although as a group the instructors consumed a sufficient amount of fluid according to the recommendations, some of them drank nothing at all in that time frame, so there is clearly a discrepancy in levels of awareness of the need to drink prior to a heat exposure. Here again there seems to be a need to educate the instructors as to how they should prepare for work in the heat.

When a comparison was made between advocated and non-advocated drinks, the instructors consumed significantly more advocated drinks. The beverages that often contributed to the non-advocated group were canned fizzy drinks that were provided for the instructors. The reasons for avoiding such drinks are detailed below, and since these drinks are a provision of the Fire Service, it would be possible to supply an...
advocated type of beverage instead. However, drinking the ‘non-advocated’ fluids is generally better than drinking nothing at all (with the exception of alcohol).

There are a variety of reasons for advocating and advising against consuming certain beverages in preparation for and during work in the heat. These are discussed at length in Section 7.4.4 and should be referred to. Most obviously, alcohol must not be drunk immediately prior to and during heat exposure because of intoxication and its associated risks in the workplace. However, consuming alcohol the night prior to heat exposure means that fire training instructors are likely to begin the day of training in a state of hypohydration. Indeed, six out of eight subjects consumed alcohol the night prior to this experiment.

Section 7.4.4 details the main reasons for advising against excessive use or reliance on carbonated beverages and oral rehydration solutions. The advantages and disadvantages of the use of sports drinks during firefighting training are also discussed. However, whereas the provision of sports drinks during training for firefighter recruits was not thought necessary in Chapter 7, consuming sports drinks, in addition to water, may be a convenient and effective way for fire training instructors to meet their fluid and carbohydrate needs throughout repetitive heat exposures. The physiological demands on the instructors are greater than that on the recruits during exposure in the firehouse, as they are required to remain inside for the whole duration of the training session. However, as discussed in Section 7.4.4, there are drawbacks in consuming too much carbohydrate-electrolyte solution, and this should be balanced with the provision of cool, palatable, flavoured and lightly salted fluids.

8.4.5 Subjective measures
Mean subjective ratings of thermal sensation mirrored the objective measure of $T_{\text{am}}$, and also the pattern of heat exposures, so that the second heat exposure elicited a lower mean thermal sensation rating because it was shorter and slightly cooler. The increases in $T_{\text{am}}$ over the heat exposures, and consequent increase in thermal sensation ratings, are concomitant with high levels of sweat loss, as strain is put on the thermoregulatory and cardiovascular systems to regulate core temperature and maintain plasma volume, respectively.
The dizziness and nausea scales seemed less sensitive to the physiological changes that the subjects experienced, perhaps indicating that they were not sufficiently hypohydrated to report such feelings.

8.4.6 Eating patterns
Since many of the instructors eat on the station, it would be logical to pass on nutritional information to personnel such as the kitchen staff. Also, it would be pertinent to advise the instructors on dietary matters in order that they could observe such practices at home, for example, the day before heat exposure.

8.4.7 Exercise patterns
In addition to fluid replacement regimes during heat exposure, fire training instructors should be made aware of the importance of replacing fluid lost through sweating during leisure time, as a failure to do so may result in arriving on duty in a hypohydrated state.

8.4.8 Knowledge of hydration issues
As in Chapter 7, individuals noted this information down. No subject had received any official training or advice regarding hydration matters. Most individuals were aware of the need to drink following heat exposure, but few were informed on the need to intake sufficient fluids prior to and during heat exposure. One subject said that he attempted to drink throughout the heat exposure, but this was difficult for two reasons: firstly because of the nature of the job, so that to drink means exiting the firehouse, which is not necessarily possible; and secondly, this subject was a stoker who was exposed to the highest levels of heat, and he found it hard to consume the equivalent amount of fluid that he lost in sweat. In addition, it is the author’s view that there seemed quite a ‘macho’ attitude apparent, where some of the instructors deemed the need to drink, or not, as a measure of ability. It is clear that if fire training instructors are not aware of what to drink and the need to drink regularly prior to, during and following heat exposure, they will not be able to impart such knowledge to trainees.
8.4.9 Summary of discussion

- Subjects' $T_{an}$ exceeded the limits provided in the only working standards available. Since it is quite feasible that an additional heat exposure may have taken place during the day's training, heat strain may have occurred.

- There was a large range in sweat loss between subjects, and those having lost most sweat are likely to have experienced symptoms such as impatience, apathy, difficulty in concentrating and physiological regulatory problems during heat exposure; this situation is clearly unacceptable in the job of a fire training instructor.

- A delay in reflection of hydration state was apparent in the urine measures used to monitor dehydration. Therefore, caution should be exercised in the use of such measures, so that a later sample may be a more accurate representation of present hydration state, and monitoring should take place over a longer period of time than just the actual day of training.

- With the exception of thermal sensation, subjective responses were not very sensitive. Although sweat loss was significant during each session, it took until the end of the day to elicit a significant thirst sensation.
8.5 Conclusions

- The mean volume of fluid consumed by the fire training instructors never replaced that lost as sweat during heat exposures, or reached the recommended levels of fluid intake at certain times prior to, during and following heat exposure (with the exception of one time point).

- The recorded excessive rises in temperature, negative water balance and high, fluctuating urine variables can in part be attributed to insufficient fluid intake as well as the heat exposure.

- No subject had received any official training or advice regarding hydration matters. Most individuals were aware of the need to drink following heat exposure, but few were informed on the need to intake sufficient fluids prior to and during heat exposure.

8.6 Recommendations

- Fluid replacement regimes should include the provision of cool, palatable liquids, which should be easily accessible.

- Education and training as to what to drink (and what to avoid), when and why. If fire training instructors are unaware of such procedures, it is unlikely that they will impart this information to trainees.
Chapter 9
Chapter 9

THE EFFECT OF A CONTROLLED DRINKING REGIME ON THE HYDRATION STATE OF FIREFIGHTER INSTRUCTORS

9.1 Introduction
The study carried out in Chapter 8 demonstrated that the fire instructors that were observed did not replace body water lost as sweat during their work in the firehouse, and they consumed significantly less fluid than is recommended for work in the heat. In addition, these fire instructors spent longer in the firehouse, and had been given no guidelines by their respective brigades concerning hydration during work in the heat. Therefore, the study in this chapter aimed to introduce controlled drinking regimes during the simulated work of fire training instructors, and observe any physiological or psychological effects of doing so compared to an ad libitum drinking regime. It is hoped that this will determine the usefulness of implementing such a regime in practice.

9.2 Method
9.2.1 Subjects
Eight male fire training instructors from three Fire Services took part in the study on three different occasions, each two weeks apart. The subjects were not the same as those in Chapter 8. The study took place in the Human Thermal Environments Laboratory (HTEL) at Loughborough University. Subjects completed HTEL and Loughborough University health screen questionnaire (Appendix 1), before written informed consent was obtained. Subjects were asked to visit the laboratory prior to the study in order to familiarise them with the surroundings and the experimental procedure; they were made aware that the study involved three days of heat exposure, but were not informed of the three different drinking conditions. Anthropometric measures were also taken on this occasion.

Anthropometric measurements of height, weight and percentage of body fat were taken (according to the equipment and techniques described in Section 2.2.1), and
subject age was also noted. Subjects had a (mean ± SD) height of 181.6 ± 2.3 cm, weight of 85.6 ± 5.6 kg, age of 38.5 ± 8.2 years, percentage body fat of 20.1 ± 4.8 % and number of years experience of 16.7 ± 11.0 years.

9.2.2 Experimental design
The experiment was a repeated measures balanced design, so that subjects took part in the study on three occasions in a different order (incomplete Latin square design), each separated by two weeks. The experimental sessions always took place in the morning to control for circadian rhythm patterns. Subjects were required to enter a thermal chamber and carry out tasks that were representative of the job of a fire training instructor in a firehouse (this was verified by the Fire Service College, Moreton-In-The Marsh, UK). The experimental day consisted of two exposures to heat, as is often the case for fire training instructors during firehouse work. Each exposure lasted 37 minutes, followed by a rest period of 45 minutes before a second exposure was undertaken.

9.2.3 Conditions
The three drinking conditions were as follows: *ad libitum* drinking (AL), a recommended drinking pattern (REC) and a modified recommended drinking pattern (MIX). These conditions are detailed below.

The AL condition consisted of the subjects drinking their own preference of liquid and volume, at any time prior to, during and following the experimental period. All fluid consumed was recorded to give type, volume and timing. Beverages such as tea, coffee and water, which are normally available in a building near the firehouse during training, were provided in a room adjacent to the experimental area. Subjects were told of the availability of these beverages, but were not encouraged any further to drink them. Subjects were permitted to consume any fluids they had brought themselves, as long as they were recorded. Subjects were permitted to take drinks into the chamber if they so wished.

The REC condition consisted of providing subjects with a set amount of fluid to consume during the experimental day, as specified in current recommendations for
working in the heat (ACSM, 1996; ACGIH, 1996; Nevola, 1998; NIOSH, 1986). Such guidelines recommend that persons exposed to heat should drink at least 500 ml of liquid 2 hours prior to exposure, 300 ml (1.5 cup-fulls) 15-20 minutes prior to heat exposure, and 200 ml every 20 minutes during exposure to heat. It is also recommended that at least 1 litre of fluid is consumed in the half-hour following heat exposure. The recommended drink is one that is:

- Flavoured and lightly salted to suit optimal acceptance and palatability
- Pre-calculated to meet requirements in terms of volume and positioning
- Cool
- Available in containers which do not limit the rate at which the beverage can be consumed
- If continual heat exposure is expected to last for more than an hour, a carbohydrate electrolyte drink, which does not affect the rate at which fluid is emptied from the stomach (< 8% carbohydrate), should be consumed. (This was not the case in the present study).

Therefore, subjects were provided with a chilled orange flavoured solution with 0.2 % carbohydrate and 21.4 mmol.L⁻¹ NaCl at the following times:

- 500 ml 2 hours before heat exposure 1
- 300 ml 15-20 minutes before heat exposure 1
- 200 ml every 20 minutes during heat exposure 1, the rest break (with the exception of 300 ml 15-20 minutes before heat exposure 2) and heat exposure 2
- 1000 ml after heat exposure 2 (within 30 minutes of exiting the thermal chamber)

The MIX drinking condition consisted of exactly the same regime as the REC condition above, except that the fluid consumed during the heat exposures was chilled water rather than an orange flavoured solution.

The subjects were not told the aim of the experiment until it was complete. Similarly, they were not informed in advance that the three days would differ in terms of the amount of fluid they would consume. The subjects were asked not to discuss the
experiment amongst each other, and were not made aware of the possible benefits or drawbacks of each of the drinking conditions.

9.2.4 Clothing

Each subject was clad in full firefighter’s kit, including SCBA, during the heat exposures. All subjects wore fire kit over standardised clothing (Plate 9.1), with the exception of underpants, which were the subjects’ own. The fire kit was a two-piece multilayer turnout suit designed to fulfil European Standard EN 469 (1994). The entire ensemble consisted of:

- cotton underpants and cotton rich socks
- working rig trousers and polo-shirt
- fire boots, fire trousers and fire tunic
- protective fire hood, helmet with skirt down and fire gloves
- SCBA (including full face mask and cylinder)

The complete clothing ensemble weighed (mean ± SD) 8.514 ± 0.236 kg.

Plate 9.1: Subjects in progressive states of dress prior to a heat exposure

9.2.5 Experimental procedure

Air temperature ($t_a$), radiant temperature ($t_r$), relative humidity (rh) and air velocity ($v$) (mean ± SD) in the thermal chamber during the first and second heat exposures are shown in Table 9.1. These parameters (with the exception of air velocity) were also measured during the rest break.
Table 9.1: Mean (+ SD) air temperature and relative humidity in the thermal chamber

<table>
<thead>
<tr>
<th></th>
<th>$t_a$ (°C)</th>
<th>$t_c$ (°C)</th>
<th>$v$ (m s$^{-1}$)</th>
<th>rh (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First heat exposure</td>
<td>45.3 ± 0.4</td>
<td>46.2 ± 0.6</td>
<td>0.26 ± 0.05</td>
<td>51.8 ± 1.3</td>
</tr>
<tr>
<td>Rest break</td>
<td>21.3 ± 0.4</td>
<td>21.9 ± 0.8</td>
<td>-</td>
<td>56.3 ± 0.4</td>
</tr>
<tr>
<td>Second heat exposure</td>
<td>46.1 ± 0.6</td>
<td>46.8 ± 0.2</td>
<td>0.24 ± 0.03</td>
<td>52.3 ± 1.7</td>
</tr>
</tbody>
</table>

The subjects completed a set of four exercises during each heat exposure in the thermal chamber. Upon entry into the chamber, the subjects sat at rest for a five minute acclimation period. The subjects were then asked to complete the first of four exercises, which lasted for five minutes. Each subject carried out the exercises in a different order. The exercises carried out in the experiment were (Plate 9.2):

- light stepping (20 steps per minute)
- walking (at 1.6 mph)
- light stepping (20 steps per minute)
- manual dexterity task (connecting and breaking hose couplings)

Plate 9.2: Exercises carried out during the experiment: walking on the treadmill, light stepping and manual dexterity (hose coupling) tasks

Following the first five minute exercise task, the subjects were given a three minute rest period before the next exercise in the sequence. This pattern of five-minute exercise / three-minute rest continued until all subjects had completed all four exercises, and was the case for all conditions.
9.2.6 Measurements

In the 48 hours prior to the first experimental day, subjects were asked to record everything that they ate and drank (time, type and quantity), as well as any activity they undertook (type, duration and intensity). Subjects were asked to repeat this pattern for the 48 hours prior to the second and third experimental days in order that they arrive in the same state of hydration (with the exception of some of the requirements of the REC and MIX drinking regimes).

Subjects were asked to follow the same procedure with regards to eating during the experimental days, and eating, drinking and activity in the six hours following the experimental periods.

Subject $T_{au}$, $T_{sk}$ and HR were measured every minute during the heat exposures using the equipment and techniques described in Section 2.2.3. Subject weight in shorts and of the full fire kit separately (to be used to calculate sweat loss ($Sw_t$), sweat rate ($Sw_R$), sweat trapped in clothing ($Sw_t$) and sweat evaporated ($Sw_{evap}$)) were determined using the weighing scales and technique described in Section 2.2.1.

Urine samples were taken at seven intervals throughout the experimental day. Urine was analysed for specific gravity ($U_{sg}$), colour ($U_{col}$) and osmolality ($U_{osm}$), using the equipment and techniques described in Section 4.2.6.

- On arrival at the laboratory
- Immediately before heat exposure 1
- Immediately after heat exposure 1
- Immediately before heat exposure 2
- Immediately after heat exposure 2
- 1 hour after heat exposure 2
- 6 hours after heat exposure 2

The SCBA air cylinder is equipped with a pressure gauge, showing the amount of air left in the cylinder. By taking a reading from this gauge it was possible to measure the rate at which each subject was using air. This gives an indication of the work rate
of each subject. Weighing the cylinder may have been more accurate, but this was not practical, as it would have disrupted flow of work.

Subjective measures were taken, as in Section 7.2.3. In addition, subjects were asked about their feelings of light-headedness (Figure 9.1) throughout the heat exposures. Measures were taken at the beginning of every exercise / rest period and at the end of the heat exposure.

<table>
<thead>
<tr>
<th>3</th>
<th>Very light-headed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Light-headed</td>
</tr>
<tr>
<td>1</td>
<td>Slightly light-headed</td>
</tr>
<tr>
<td>0</td>
<td>Not light-headed</td>
</tr>
</tbody>
</table>

*Figure 9.1: Light-headedness scale*

9.2.7 Statistical Analyses

Two way ANOVA's and Tukey's HSD were used to analyse differences in all measures between conditions, with the exception of measures of sensation, thirst, nausea, dizziness and light-headedness. The latter were analysed using Mann-Whitney U tests. Significance was determined at the $p < .05$ confidence level (where the Bonferroni criterion was applied, the significance will be denoted thus: $p^b < .05$), and all terms were expressed as the mean $\pm SD$.

9.3 Results

9.3.1 Aural temperature

Aural temperatures throughout both heat exposures for each of the three conditions are shown in Figure 9.2. There was no significant difference in aural temperature between conditions at time = 0 min in the first heat exposure. Throughout the exposure (from time = 6 min onwards), AL temperatures were higher than both REC and MIX. There was a significant difference between the conditions at time = 20 min ($p^b < .05$), where temperatures in the REC and MIX conditions were attenuated following fluid intake. At this time, the differences were between AL and REC ($p < .05$), and AL and MIX ($p < .05$), but not between REC and MIX, although from this point on, MIX temperature remained lower than the other two conditions. At the end
point of the first heat exposure (time = 37 min), there was a significant difference between all the conditions ($p^b < .05$).

Following the rest break, at the beginning of the second heat exposure (time = 01:15 hr min), aural temperature in the REC and MIX conditions still remained lower than that in the AL condition, but this difference did not become significant ($p = .067$ at time = 01:15 hr min; $p = .059$ at time = 01:40 hr min; and $p = .053$ at time = 01:52).

The temperature means and ranges are given in Table 9.2.

Table 9.2: Mean aural temperature for two heat exposures across all conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Heat exposure 1</th>
<th>Heat exposure 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (±SD)</td>
<td>Range</td>
</tr>
<tr>
<td>AL</td>
<td>37.5 ± 0.7</td>
<td>36.3 – 38.7</td>
</tr>
<tr>
<td>REC</td>
<td>37.3 ± 0.5</td>
<td>36.4 – 38.1</td>
</tr>
<tr>
<td>MIX</td>
<td>37.2 ± 0.4</td>
<td>36.4 – 37.9</td>
</tr>
</tbody>
</table>

![Figure 9.2: Mean aural temperature response throughout heat exposures 1 and 2 (T<sub>au</sub> was not measured during the rest break, and the dashed line signifies the drop in temperature between the end of heat exposure 1 and the beginning of heat exposure 2)
9.3.2 Mean skin temperature

Mean skin temperatures throughout both heat exposures for each of the three conditions are shown in Figure 9.3. There was no significant difference in skin temperature between the conditions at the beginning of the first heat exposure, but from time = 7 min to the end of the heat exposure, temperatures for REC and MIX were lower than that for AL. In particular, skin temperature was attenuated in the REC and MIX conditions following both fluid intakes (time = 18 and 34 min). There was a significant difference in skin temperature at time = 25 ($p < .05$). The differences were between AL and REC ($p < .05$) and AL and MIX ($p < .05$). However, the differences between the conditions were not significant by the end of the first heat exposure.

Skin temperature in the REC and MIX conditions remained similar and lower than that in the REC condition for the start of the second heat exposure ($p < .05$). The significant differences were between AL and REC ($p < .05$) and AL and MIX ($p < .05$). This pattern continued throughout the heat exposure, but the differences were not significant.

![Figure 9.3: Mean skin temperature response throughout heat exposures 1 and 2 (Tsk was not measured during the rest break, and the dashed line signifies the drop in temperature between the end of heat exposure 1 and the beginning of heat exposure 2)](image-url)
9.3.3 Heart rate

Mean heart rates for each condition are shown in Figure 9.4. Heart rate means and ranges are given in Table 9.3. The graph clearly reflects the periods of activity and rest during each heat exposure. Heart rates in the REC and MIX conditions started lower than that for AL at the beginning of the first heat exposure, but this difference was not significant. Heart rates in the REC and MIX conditions were both attenuated following fluid intake (time = 18 mins), but the attenuation was greater in the MIX condition. There was a significant difference between conditions at time = 25 mins ($p^b < .05$). The differences were between: AL and REC ($p < .05$) and AL and MIX ($p < .05$). This pattern continued to the end of the first heat exposure, where there remained a significant difference between the conditions ($p^b < .05$). The differences were between: AL and REC ($p < .05$) and AL and MIX ($p < .05$).

Heart rates in the REC and MIX conditions remained similar and lower than AL for the start of the second heat exposure, so that there was a significant difference between the conditions ($p^b < .05$). The differences were between: AL and REC ($p < .05$) and AL and MIX ($p < .05$). Heart rates were attenuated in both REC and MIX conditions following fluid intake (time = 01:33 hr min), but the attenuation was greater for the MIX condition. There was a significant difference between conditions at time = 01:40 hours mins ($p^b < .05$). The differences were between: AL and REC ($p < .05$) and AL and MIX ($p < .05$). This pattern continued to the end of the second heat exposure, where there remained a significant difference between the conditions ($p^b < .05$). The differences were between: AL and REC ($p < .05$) and AL and MIX ($p < .05$).
Figure 9.4: Mean heart rate response throughout heat exposures 1 and 2 (HR was not measured during the rest break, and the dashed line signifies the drop in HR between the end of heat exposure 1 and the beginning of heat exposure 2)

Table 9.3: Mean heart rate for two heat exposures across all conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Heat exposure 1</th>
<th>Heat exposure 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (±SD)</td>
<td>Mean (±SD)</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>Range</td>
</tr>
<tr>
<td>AL</td>
<td>152 ± 25</td>
<td>160 ± 22</td>
</tr>
<tr>
<td>REC</td>
<td>126 ± 17</td>
<td>125 ± 20</td>
</tr>
<tr>
<td>MIX</td>
<td>123 ± 15</td>
<td>119 ± 15</td>
</tr>
<tr>
<td></td>
<td>93 – 181</td>
<td>107 – 186</td>
</tr>
<tr>
<td></td>
<td>87 – 151</td>
<td>93 – 162</td>
</tr>
<tr>
<td></td>
<td>88 – 143</td>
<td>91 – 147</td>
</tr>
</tbody>
</table>

9.3.4 Sweat variables

The mean total sweat losses for each of the conditions are shown in Figure 9.5. These totals comprise of mean sweat evaporated and mean sweat trapped in clothing. In heat exposure one there was a significant difference between the conditions in total sweat loss (p < .05). The differences were between: AL and REC (p < .05) and AL and MIX (p < .05). During the second heat exposure, sweat loss was greatest in the MIX condition, which was similar to the REC condition, and least in the AL condition. However, these differences were not significant.
Figure 9.5: Total sweat loss for each condition for both heat exposures. The totals comprise of sweat evaporated and sweat trapped clothing.

9.3.5 Drinking patterns

All drink consumed (volumes and time consumed) by subjects during the day of testing through to 6 hours after heat exposure was recorded. As in previous chapters, the mean actual volume of beverages consumed (in the AL condition) is plotted against the recommended volumes of fluid to drink during these times (REC and MIX conditions) in Figure 9.6. The time scales for drinking are given along the x axis.
To determine whether the instructors consumed enough fluid overall in the AL condition, according to the recommendations (the REC and MIX conditions – same volume), total fluid intake over the day was compared between conditions. There was a significant difference between the AL condition and REC and MIX conditions \( (P < .05) \), so during testing in the AL condition the instructors consumed significantly less fluid than is recommended (for this duration, the recommendation would be 2.7 litres, but the instructors consumed 1.3 litres). A further comparison was made to establish whether the instructors consumed enough extra fluid in the six hours following heat exposure in the AL condition to equate with the recommended fluid intake for the period of work in the heat. The total daily fluid intake including that in the six hours following heat exposure was significantly less than the recommendations \( (p < .05) \) (the instructors consumed 2.4 litres, for the duration of the testing and in the 6 hours following).

To identify whether there was a problem with fluid intake during heat exposure in the AL condition, a comparison was made of the mean values of the first and second heat exposures. The average fluid intake over both heat exposures was significantly less \( (p\)
than the recommended value, since the instructors did not consume any fluids at all in this period. To establish if there was a problem with drinking during rest in the AL condition, a mean was taken of the 15 minutes prior to each heat exposure and compared to the recommendation (the 2 hours prior to heat exposure could not be analysed, as the second set was confounded by consisting of heat exposure 1 and rest data between the two heat exposures). During rest there was significantly less fluid consumed than is recommended ($p < .05$) (the recommendation is 300 ml, but the instructors consumed 152 ml). Since all the instructors knew they would be participating in two heat exposures during the day, their drinking patterns in the 2 hours prior to the first heat exposure in the AL condition were compared to the recommendations. The volume of fluid consumed was not significantly different from the recommended amount.

### 9.3.6 Urine measures

Urine samples were taken at seven intervals throughout the experimental day (see Section 9.2.6) to assess hydration state. They were analysed for colour, specific gravity and osmolality. To determine whether the drinking regimes (which began before arrival at the laboratory) made a difference at the start of the day of heat exposure, the first urine sample was compared between conditions. To assess if the drinking regimes made a difference immediately prior to both heat exposures, a mean was taken of the second and fourth urine samples and compared between conditions. This process was repeated with the third and fifth urine samples to determine if the drinking regimes made a difference immediately following both heat exposures. Finally, the seventh sample was compared between conditions to determine which drinking regime allowed greater recovery of hydration state six hours after heat exposure.

Mean values of urine colour for each of the seven samples are shown in Figure 9.7. Although values for REC and MIX were lower than those for AL in the first sample, the difference was not significant. There was a significant difference between conditions for the mean of samples 2 & 4 ($p < .05$). The differences were between: AL and REC ($p < .05$) and AL and MIX ($p < .05$). There was no significant difference between the conditions for the mean of samples 3 & 5, because although
values for AL were much higher than values for REC and MIX in sample 3 (post heat exposure 1), all values were similar for sample 5 (post heat exposure 2). For sample 7 there was a significant difference between the conditions ($p^b < .05$), and these differences were between AL and REC ($p < .05$) and AL and MIX ($p < .05$).

Mean values of urine specific gravity for each of the seven samples are shown in Figure 9.8. There were significant differences between conditions in all the sample combinations analysed (sample 1, mean of samples 2 & 4, mean of samples 3 & 5, and sample 7) ($p^b < .05$). The differences were all between AL and REC ($p < .05$) and AL and MIX ($p < .05$). For sample 7, there was also a difference between REC and MIX ($p < .05$).

![Figure 9.7: Urine colour values of the seven samples taken throughout the day of testing for each of the conditions](image-url)
Figure 9.8: Urine specific gravity values of the seven samples taken throughout the day of testing for each of the conditions.

Figure 9.9: Urine osmolality values of the seven samples taken throughout the day of testing for each of the conditions.
Mean values of urine osmolality for each of the seven samples are shown in Figure 9.9. There were significant differences between conditions in all the sample combinations analysed (sample 1, mean of samples 2 & 4, mean of samples 3 & 5, and sample 7) ($p^b < .05$). The differences were all between AL and REC ($p < .05$), AL and MIX ($p < .05$) and REC and MIX ($p < .05$), except for sample 1, where there was no difference between REC and MIX.

9.3.7 Cylinder air pressure
The rate at which cylinder air pressures fell and therefore air was used, which are representative of the rate at which the user is working, are plotted for all conditions in Figure 9.10. There was no significant difference in air pressure between conditions at the start of each heat exposure, as the cylinders are always filled to capacity prior to use. Throughout the course of each of the heat exposures, cylinder air pressure fell at a much greater rate in the AL condition than both REC and MIX conditions, which fell at similar rates. Cylinder air pressure was analysed after exercise 2 and after exercise 4 in both heat exposures, and there were differences between the conditions at all four of these times ($p^b < .05$). The differences were always between AL and REC ($p < .05$) and AL and MIX ($p < .05$), and there was never a significant difference between the REC and MIX conditions.

9.3.8 Subjective measures
Subjective measures were taken at the beginning of every exercise or rest period and at the end of the heat exposure, and are shown in Figures 9.11-9.15. Measures taken at the beginning of the heat exposure, the beginning of exercise 3, and the end of rest 4 were analysed here. The key to each of the subjective scales is shown at the end of this section.
Responses of thermal sensation for all conditions are shown in Figure 9.11. Thermal sensation increased at a similar rate for all conditions throughout both heat exposures, and there was no significant difference between the conditions. Responses for the REC and MIX conditions were rated as 'very hot' (the highest rating) by rest 3 in the first heat exposure and exercise 3 in the second heat exposure, whereas subjects did not rate their thermal sensation as being 'very hot' in the AL condition until exercise 4 and rest 3 respectively. It is clear that an extension of the thermal sensation scale to include 'extremely hot' would have been useful in this study.
Subjective responses of thirst for all conditions are shown in Figure 9.12. Responses were very different between the AL condition and the other two conditions, with the former always having a higher rating. At the beginning of both heat exposures, at the beginning of exercise 3 and the end of rest 4, there were significant differences between the conditions. The differences were always between AL and REC \( (p^b < .05) \) and AL and MIX \( (p^b < .05) \), and there was never a significant difference between the REC and MIX conditions.

Subjective responses of nausea for all conditions are shown in Figure 9.13. There were no feelings of nausea in any of the conditions until exercise 1 in both heat exposures. From here, feelings of nausea rose steadily in the AL condition until the end of both heat exposures. However, feelings of nausea rose steeply in the REC condition immediately following fluid ingestion in rest 2 in both exposures. These responses began to fall as both exposures continued, but were then renewed following fluid ingestion in rest 4. Reported feelings of nausea were very low all the way through both heat exposures in the MIX condition, and these disappeared following both fluid intakes in both heat exposures. There were significant differences between the conditions at beginning of exercise 3 and the end of rest 4 in both heat exposures. The differences were between AL and REC \( (p^b < .05) \), AL and MIX \( (p^b < .05) \) and REC and MIX \( (p^b < .05) \).
Figure 9.12: Mean subjective responses of thirst for all conditions

Figure 9.13: Mean subjective responses of nausea for all conditions
Subjective responses of dizziness for all conditions are shown in Figure 9.14. There were no feelings of dizziness in any condition until rest 1 in heat exposure 1 and exercise 1 in heat exposure 2. There were rarely any feelings of dizziness in the REC and MIX conditions, but they built up gradually throughout both heat exposures in the AL condition. In heat exposure 1, there was a significant difference between conditions at beginning of exercise 3; this was between AL and REC ($p^b < .05$) and AL and MIX ($p^b < .05$). There was still a significant difference between conditions by the end of rest 4; this was between AL and REC ($p^b < .05$) and AL and MIX ($p^b < .05$). In heat exposure 2, there were significant differences between conditions at beginning of exercise 3 and the end of rest 4; these were between AL and REC ($p^b < .05$) and AL and MIX ($p^b < .05$).

![Figure 9.14: Mean subjective responses of dizziness for all conditions](image)

Subjective responses of light-headedness for all conditions are shown in Figure 9.15. There were no feelings of light-headedness in any of the conditions until exercise 3 in the first heat exposure and rest 1 in the second heat exposure. Feelings of light-headedness were predominantly reported in the AL condition. There were differences between the conditions at the end of rest 4 for both exposures, and also at beginning of exercise 3 for the second exposure. The differences were always between AL and REC ($p^b < .05$) and AL and MIX ($p^b < .05$).
**Figure 9.15:** Mean subjective responses of light-headedness for all conditions

**Key to use scales:**

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<td>Warm</td>
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<tr>
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<tr>
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<td>Cool</td>
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<tr>
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</tr>
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9.4 Discussion

9.4.1 Aural temperature

The rise in aural temperature in the REC and MIX conditions was attenuated by drinking on both occasions during the first heat exposure, whereas temperature continued to rise in the AL condition. This attenuation was greater in the MIX condition, but both types of drinking regime produced significantly lower temperatures at the end of the exposure than ad libitum drinking. Numerous investigators report that ad libitum water intake results in incomplete water replacement or 'voluntary' dehydration during exercise in the heat (Adolph, 1947; Engell et al, 1987). There is decreased exercise thermoregulation at 1% body water loss (Greenleaf & Harrison, 1986), which concurs with the continual rise in temperature in the AL condition. Even though subjects did not reach 1% body weight loss within the first heat exposure, the urinary indices of $U_{sg}$ and $U_{osm}$ showed that subjects in the AL condition were less well-hydrated at the beginning of the exposure than in the other conditions, which may have had a cumulative effect. Also, consuming chilled fluids throughout the exposure will have had a cooling effect from within on subjects in the REC and MIX conditions. Aural temperature may have slowed more in the MIX condition than REC due to a combination of physiological and psychological phenomena. Physiologically, the intake of water during exercise may have reduced plasma osmolality to a greater extent than the intake of the orange flavoured solution, thereby reducing the demand on the hypothalmic osmoreceptors to respond by causing water to shift from the intracellular to the extracellular compartment. Psychologically, the highly significant rise in nausea following ingestion of orange flavoured solution in the REC condition may provide a further explanation as to the difference in response in the two drinking conditions.

In the second heat exposure, although aural temperatures in the REC and MIX conditions were closer to baseline readings and remained lower than AL throughout, the differences were not significant, and drinking was less able to cause an attenuation in temperature. This is because as dehydration progresses and plasma volume drops, sweating is reduced and thermoregulation becomes progressively more difficult. In hypohydration, an elevated core temperature is related to a reduction in both sweating and blood flow to the skin (Fortney et al, 1981b; Nadel et al, 1980). However,
throughout the experimental day, which simulated the work of a fire training instructor, the introduction of drinking regimes reduced aural temperature response, and to a greater extent in the MIX condition.

9.4.2 Mean skin temperature
Mean skin temperature responses were similar to that of aural temperature for each condition, but the differences between each were less. Due to the high insulating properties of the firekit, thermoregulation was difficult regardless of drinking condition. More sweat was trapped in clothing than was evaporated in all conditions, and therefore skin cooling was hampered, as discussed by Graveling (1998). It is likely that humidity levels in the clothing micro-environment became very high, which prevented further sweat evaporation.

9.4.3 Heart rate
Heart rates in the REC and MIX conditions were lower than those for the AL condition at the beginning of the first heat exposure, as the drinking regimes began two hours prior to heat exposure. The drinking regimes continued to effectively attenuate heart rate throughout both heat exposures, and recovery between exposures was markedly better in the two drinking conditions. As dehydration progressed in the AL condition (no subject consumed any fluid during heat exposure in the AL condition), the drop in plasma volume, and therefore reduction in sweating would have caused thermoregulation to become progressively more difficult. The increased heart rate can be attributed to a reduced central blood volume that leads to a lower ventricular filling pressure and stroke volume. Lower heart rates in the MIX condition compared to the REC condition are likely to be due to the increased feelings of nausea in the REC condition, which did not occur following the ingestion of water in the MIX condition.

9.4.4 Sweat variables
In both heat exposures more sweat was produced in the REC and MIX conditions than in the AL condition, thereby providing a greater capacity to dissipate heat through evaporative cooling from the skin. Although such evaporative cooling was restricted due to the thickness of the fire kit, more sweat was evaporated in the drinking
conditions. Since subjects did not replace water lost as sweat in the AL condition, it is likely that sweating was reduced in order to help maintain plasma volume for the duration of the heat exposure and exercise. In the REC and MIX conditions, however, more fluid was available as sweat to aid in thermoregulation.

9.4.5 Drinking patterns

Subjects in the AL condition consumed significantly less fluid throughout the day of heat exposure then is recommended (ACSM, 1996; ACGIH, 1996; Nevola, 1998; NIOSH, 1986), and did not manage to replace the deficit in the six hours following heat exposure. No subjects drank during heat exposure in the AL condition. It is likely that this was due to the inconvenience of having to remove the face mask (and therefore helmet) to do so. During a hot wear training session at the firehouse it would not be safe to attempt to drink whilst inside the building. However, when the instructor / student ratio is high enough, it would be possible for each of the instructors to exit the firehouse, ingest a drink and re-enter. A short break of this sort would also contribute to the alleviation of heat stress. Subjects in the AL condition also consumed significantly less in the 15-20 minutes prior to each heat exposure than is recommended. It is likely that they were pre-occupied with preparation of their PPE and SCBA, and did not take the time to consume fluids. It is therefore essential that fire instructors attempt to work in taking fluid onboard with their kit preparation. The instructors managed to consume an amount of fluid that was not significantly different from the recommendations in the two hours prior to the day of heat exposure. However, just under half of this volume constituted drinks that were ‘non-advisable’ for use in preparation for or during heat exposure. This creates a training issue, so that fire instructors should be made aware of the types of drinks they should consume during this time.

9.4.6 Urine measures

Urine measures in all conditions reflected the general process of dehydration that occurs during and following heat exposure with exercise. However, urine variables in the AL condition were far more elevated than those in the REC and MIX conditions, and this agrees with previous studies where *ad libitum* water intake resulted in incomplete water replacement or ‘voluntary’ dehydration during exercise in the heat
(Adolph, 1947; Engell et al, 1987). Although variable values were much greater in the AL condition than the drinking conditions in most of the samples, this pattern differed in samples 5 and 6, where hydration state seemed to improve in the AL condition immediately following and one hour following the second heat exposure. It is likely that as dehydration progressed in the AL condition, the body may have moved fluid from the intra- to the extra-cellular space in order to maintain plasma volume. The stimulus for this originates in the hypothalamic osmoreceptors that monitor the ECF’s osmolality. Hypohydration has long been recognised as a contributing factor to heat illness (Goldman, 1988; Hubbard & Armstrong, 1988; Leithead & Lind, 1964; and Shibolet et al, 1976). Therefore, during heat exposure, periods of physical work and at times when fluid intake is not adequate to balance water lost through sweating, several homeostatic mechanisms are activated to meet the thermoregulatory, cardiovascular and metabolic demands of the body, thereby conserving vital fluids; the production of concentrated urine is one of the early indications of such conservation. The hypothalamus’ posterior pituitary neurosecretory system responds to these multiple and conflicting needs for fluid by releasing water conserving antidiuretic hormone (ADH) in an attempt to reduce urinary fluid loss to preserve plasma volume. Also in response to a drop in PV/blood pressure, the hormone renin is secreted. Increased renin secretion, through a complex series of events involving angiotensin I and II and aldosterone, brings about increased sodium reabsorption. The ultimate benefit of this salt retention is its accompanying osmotically induced water retention, which helps restore the PV and blood pressure. Therefore, it is quite usual for acute heat exposure, fluid restriction or exercise stress to elicit marked increases in circulating levels of hormones such as ADH, angiotensin I and aldosterone (Francesconi et al, 1987).

The changes in urine variable values within and between conditions and the processes described above demonstrate that effective drinking regimes go some way towards reducing the process of dehydration and therefore heat stress in a fire instructors working environment. In addition, it is clear that reliance on ad libitum drinking is not adequate to support the physiological processes involved in responding to high ambient temperature loads, exercise and heavy PPE and SCBA.
9.4.7 Cylinder air pressure

The rate at which cylinder air pressures falls is representative of the rate at which the user is working. Although less air was used in the REC and MIX conditions than in AL, the mechanism for this is not clear, and may not be a direct effect. However, this is of importance during the work of a fire training instructor, as a higher work rate would indicate that the instructors had to work harder to carry out the same task, and therefore may be less able to supervise the recruits in their charge. This also transfers operationally, so that a firefighter may have less cylinder time at their disposal.

9.4.8 Subjective measures

Ratings of thermal sensation increased to the same level at the end of each exposure for all the conditions, but the rate at which they rose was slower for the REC and MIX conditions, reflecting a greater thermoregulatory capacity. Feelings of thirst rose steadily throughout each exposure in the AL condition, but disappeared following fluid ingestion in the REC and MIX conditions. Since the sensation of thirst may only be felt once the level of hypohydration has reached 1 – 2% (Nevola, 1998, Sawka 1988), and the subjects did not drink despite feeling thirsty, it is important that thirst is not relied on as a method of monitoring fluid intake for fire instructors. Feelings of nausea rose steadily in the AL condition, were removed following water intake in the MIX condition, but increased drastically following the ingestion of the orange flavoured solution in the REC condition. It seems that plain water was the best fluid to ingest during exercise, as a flavoured beverage created these feelings of nausea, and this is likely to discourage instructors from drinking regularly during their work. Feelings of dizziness and light-headedness were only a problem in the AL condition, and came on towards the end of each heat exposure. This is not an acceptable situation during the work of a fire instructor, who must be alert and aware of the actions of recruits in the firehouse, especially towards the end of a hot wear when recruits may also be suffering the effects of dehydration and heat stress.
9.5 Conclusions

- Compared to the AL condition, the two controlled drinking regimes, REC and MIX, provided a significant attenuation in aural and skin temperatures, heart rate, total ventilation, and subjective measures of thermal sensation, thirst, dizziness and light-headedness.

- Values for the above measures were generally lower in the MIX condition than the REC condition, although not always significantly. There was also an increase in subjective feelings of nausea in the REC condition immediately following the ingestion of a flavoured beverage, which was absent in the MIX condition.

- The REC and MIX conditions allowed for the production of significantly more sweat than the AL condition, thereby providing a greater capacity for heat loss.

- Urinary indices showed that hypohydration levels were significantly greater in the AL condition than REC and MIX conditions.

- Drinking patterns in the AL condition were such that they did not replace that lost as sweat and were significantly lower than recommended levels.

- Cylinder air pressure fell at a significantly greater rate in the AL condition than the REC and MIX conditions.

- The findings of this study suggest that the adoption of a controlled drinking regime during work in a firehouse may lessen the likelihood of a fire instructor incurring heat strain.
9.6 Summary of Part III

The findings of this Part were as follows:

- Chapter 6 provided background information on the purpose of firehouses, the job of a fire training instructor, and what is expected of firefighter recruits whilst training in a firehouse.

- In Chapter 7 it was found that firefighter recruits did not drink optimally during training in firehouses, but since their exposure was time limited, this did not become a major problem.

- In Chapter 8 the hydration states of fire training instructors were studied. It was found that a combination of longer exposure times (than the recruits) and not drinking optimally lead to heat strain.

- Chapter 9 studied the physiological and psychological effects of two controlled drinking regimes, compared to an *ad libitum* drinking regime, on fire training instructors. When the instructors followed the two drinking regimes, physiological and psychological measures were attenuated, compared to *ad libitum* drinking. Therefore, the adoption of such controlled drinking regimes in the workplace may lessen the likelihood of an instructor suffering heat strain. However, practical issues of implementing such a drinking regime into a working environment, for example, during firefighter training, need to be considered.
Part IV

Application of theory:

Providing practical methods of hydration control in industry
PART IV: APPLICATION OF THEORY – PROVIDING PRACTICAL METHODS OF HYDRATION CONTROL IN INDUSTRY

The aim of this section of the thesis is to provide both in depth analysis of the physiology and regulation of body fluids, and quick reference information for remaining well-hydrated during firefighting tasks (the Fire Service were used as a case study). A further aim was to identify any practical issues of implementing a controlled drinking regime into an environment such as that of a firefighter or a fire training instructor.
Chapter 10
Chapter 10

A PRACTICAL MODEL OF HUMAN WATER BALANCE

10.1 Introduction

This practical model of human water balance has been developed in order to draw together: 1) basic physiological principles; 2) recent and current experimental work on the outcomes of fluid balance studies; and 3) practical questions that are often an issue for those whose jobs involve heat exposure, or monitoring others who work in the heat, and are therefore likely to experience the problems of human fluid balance.

The structure of the model allows it to be utilised in several ways: to aid learning and more in-depth understanding of the regulation of body fluids; to make information about the complex regulatory systems of the body and the interactions between man and his environment more accessible to less academic users; as a practical aid for those who monitor workers exposed to hot conditions to assess the likely effects on body fluid balance in particular scenarios; and as a reference for drinking regimes before, during and following heat exposure. The assimilation of theory and empirical data permits the model to be used as a learning tool and as an aid in practical situations where dehydration is a likely outcome.

The structure of this chapter covers the physiology and regulation of body fluids, and then provides some worked examples of problems encountered in hot working environments. The overall aim of the chapter is to provide a thorough understanding of body water systems, which will then allow a user to provide appropriate advice for a variety of situations.

10.2 Physiology of the Body Fluids

The primary function of the kidneys is the maintenance of the normal volume and composition of the body fluids. Thus, the kidneys are responsible for the excretion of excess water, ions and waste products, as well as for the conservation of solutes important to proper body function.
10.2.1 Body water and body fluid compartments

Water is the most abundant molecular component of the body, constituting on average for 60% (range of 45-75%) of the total body weight. In an adult, this average represents approximately 42 litres of water. Since the kidneys are so efficient at regulating water balance, the water content of an individual remains fairly constant over a period of time. However, the reason for the large range in water content between individuals is primarily a function of variations in the amount of adipose tissue. At 10%, adipose tissue is the driest tissue of all and therefore has a low water content compared to other tissues. The skin is over 70% water, skeletal muscle more than 75% water, and organs such as the heart, lung and kidneys are approximately 80% water. The relatively drier skeleton is only 22% water (Table 10.1).

Table 10.1: Water content of body tissues (adapted from Skelton, 1927)

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Percentage of Water (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma</td>
<td>&gt;90</td>
</tr>
<tr>
<td>Kidney</td>
<td>83</td>
</tr>
<tr>
<td>Heart</td>
<td>79</td>
</tr>
<tr>
<td>Lung</td>
<td>79</td>
</tr>
<tr>
<td>Skeletal muscle</td>
<td>76</td>
</tr>
<tr>
<td>Brain</td>
<td>75</td>
</tr>
<tr>
<td>Skin</td>
<td>72</td>
</tr>
<tr>
<td>Liver</td>
<td>68</td>
</tr>
<tr>
<td>Skeleton</td>
<td>22</td>
</tr>
<tr>
<td>Adipose tissue</td>
<td>10</td>
</tr>
</tbody>
</table>

Therefore, since fat is the driest tissue in the body, the percentage of body weight that is water will vary inversely with the fat content of the body. Total body water (TBW) is also affected by the age and sex of the individual. In both sexes, the percentage of body weight that is water decreases with age; this can be attributed primarily to an increasing percentage of adipose tissue (Hays, 1980). In normal young adult males, TBW is about 60% of body weight, and in normal young adult females, it is about 50%. Women have a lower body water content than men, primarily because the female sex hormone oestrogen promotes fat deposition in the breasts, buttocks, and elsewhere. This not only gives rise to the typical female figure, but also endows women with a higher proportion of adipose tissue, and therefore a lower body water content.
Total body water is distributed between two major fluid compartments: the fluid within the cells, the *intracellular fluid* (ICF), which contains approximately 55% of the TBW, and the fluid surrounding the cells, the *extracellular fluid* (ECF), which contains approximately 45% of the TBW (*Table 10.2*). (The terms “water” and “fluid” are commonly used interchangeably. Although this usage is not entirely accurate because it ignores the solutes in the body fluids, it is acceptable when one considers the total volume of the fluids, since the major proportion of these fluids consists of water). The ECF compartment is further subdivided into several smaller compartments (*Table 10.2*); the most important of these compartments are *plasma*, the fluid portion of the blood, which contains about 7.5% of the TBW, and *interstitial fluid*, which includes the fluid between the cells and lymph, and contains about 20% of the TBW. Interstitial fluid, sometimes known as tissue fluid, constitutes the true internal environment in that it is the fluid that bathes the tissue cells. Only a minute proportion of the interstitial fluid is free flowing; more than 99% of it is held in gel form in the extracellular matrix. Lymph is fluid being returned from the interstitial fluid to the plasma by means of the lymphatic system, meanwhile being filtered through lymph nodes for immune-defence purposes.

Several other minor ECF compartments, which together contain only about 2.5% of the TBW, make up the *transcellular* fluid. Transcellular fluid consists of a number of small specialised fluid volumes, all of which are secreted by specific cells into a particular body cavity to perform some specialised function. Transcellular fluid includes: cerebrospinal fluid (surrounding, cushioning and nourishing the brain and spinal chord); intraocular fluid (maintaining the shape of and nourishing the eye); synovial fluid (lubricating and serving as a shock absorber for joints); pericardial, pleural, and peritoneal fluids (lubricating movements of the heart, lungs and intestines, respectively); and the digestive juices (digesting ingested foods). The term transcellular fluid is used to describe these minor ECF compartments because they are separated from the rest of the ECF by a layer of epithelial cells. Although these fluids are extremely important functionally, they represent an insignificant fraction of the total body water. Furthermore, the transcellular compartment as a whole usually does not reflect changes in the body’s fluid balance. For example, the cerebrospinal fluid does not decrease in volume when the body as a whole is experiencing a negative
water balance. This is not to say that these fluid volumes never change. Localised changes in a particular transcellular fluid compartment can occur pathologically (such as too much intraocular fluid accumulating in the eyes of a person with glaucoma), but such a localised fluid disturbance does not affect the fluid balance of the body. Therefore, the transcellular compartment can usually be ignored when one is dealing with problems of fluid balance. The main exception to this generalisation is when digestive juices are abnormally lost from the body during heavy vomiting of diarrhoea, which can bring about fluid imbalance.

<table>
<thead>
<tr>
<th>Compartment</th>
<th>Percent of total body water</th>
<th>Percent of total body weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Normal Adult Male&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Intracellular fluid</td>
<td>55</td>
<td>33</td>
</tr>
<tr>
<td>Extracellular fluid</td>
<td>45</td>
<td>27</td>
</tr>
<tr>
<td>Interstitial</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>Plasma</td>
<td>7.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Bone</td>
<td>7.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Dense connective tissue</td>
<td>7.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Transcellular</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Total body water</td>
<td>100</td>
<td>60</td>
</tr>
</tbody>
</table>

<sup>a</sup>From Edelman & Leibman, 1959  
<sup>b</sup>From Laiken & Fanestil, 1990a

### 10.2.2 Measurement of body fluid compartments

Although the volumes of the various body fluid compartments cannot be measured directly, estimates can be made using *dilution techniques*, providing useful information for experimental and clinical purposes. Such techniques use marker substances that distribute in a specific body fluid compartment. Radioactive markers or markers whose concentrations can be assayed colorimetrically are generally used. Dilution techniques (as well as other methods) can be used to estimate the volumes of TBW, ECF and plasma (*Table 10.3*). The volume of the compartment can be determined using the following equation, so that if a known quantity of such a marker X is administered and given time to distribute throughout the compartment, a sample from that compartment will show the concentration of X:
Mass of X administered

Volume of compartment = Concentration of X in compartment

\[(Eq. 10.1)\]

The dilution method may also be corrected for the amount of marker lost, for example in urine, during the period of distribution:

\[\text{Mass of X administered} - \text{mass of X lost}\]

Volume of compartment = Concentration of X in compartment

\[(Eq. 10.2)\]

<table>
<thead>
<tr>
<th>Compartment</th>
<th>Marker Substance / Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBW</td>
<td>D₂O</td>
</tr>
<tr>
<td></td>
<td>HTO</td>
</tr>
<tr>
<td></td>
<td>Antipyrine</td>
</tr>
<tr>
<td></td>
<td>Whole body impedance</td>
</tr>
<tr>
<td>ECF</td>
<td>Radioisotopes of selected ions (Na⁺, Cl⁻, Br⁻, SO₄²⁻, S₂O₃²⁻)</td>
</tr>
<tr>
<td></td>
<td>Non-metabolizable saccharides (inulin, mannitol, raffinose)</td>
</tr>
<tr>
<td>Plasma</td>
<td>¹³¹ I-Albumin</td>
</tr>
<tr>
<td></td>
<td>Evans blue dye (T-1824)</td>
</tr>
<tr>
<td></td>
<td>⁵¹Cr-erythrocytes</td>
</tr>
<tr>
<td></td>
<td>Change in plasma volume (Dill &amp; Costill, 1974)</td>
</tr>
</tbody>
</table>

**Total Body Water:** The volume of TBW is estimated using marker that distribute uniformly throughout all body fluids, such as *deuterated water* (D₂O) or *tritiated water* (HTO). The drug *antipyrine* also can be used, although it penetrates certain parts of the body water slowly and therefore tends to underestimate the TBW. Since plasma is part of the TBW, the concentration of the marker in the TBW compartment can be obtained from a plasma sample (using Equations 10.1 and 10.2).

**Extracellular Fluid:** The estimation of ECF volume with dilution methods requires markers that can freely cross the capillary endothelium but that are predominantly excluded from cells. However, no ideal marker substance for this is available (Edelman & Leibman, 1959). Radioisotopes of ions such as Na⁺, Cl⁻, Br⁻, SO₄²⁻, S₂O₃²⁻ (thiosulphate) can be used, but these enter cells to varying extents and therefore tend to overestimate the ECF volume. Non-metabolizable saccharides such as inulin, mannitol and raffinose also can be used, but these do not readily distribute throughout the entire extracellular compartment, and therefore tend to underestimate the ECF.
volume. In addition, none of the ECF markers distributes into bone water, and many are excluded from, or penetrate very slowly, dense connective tissue and transcellular fluid. Dilution methods therefore give ECF volumes that range from approximately 27% of the TBW for markers such as inulin that distribute primarily into plasma and interstitial fluid to as much as 45% of the TBW for markers such as Na\(^+\) that, while not distributing into bone water, enter cells to the same extent. Due to this large range in values obtained with different markers, the approximation that ECF contains about one-third of TBW is widely used. As with TBW, ECF contains plasma, so the concentration of a marker in the ECF can be obtained from a plasma sample.

**Plasma:** Since plasma proteins are distributed almost exclusively in the vascular compartment, markers used to measure plasma volume take advantage of this. Albumin is the most abundant (60%) and smallest of the plasma proteins, which functions primarily to regulate osmotic pressure of plasma. Therefore, the volume of plasma can be estimated using radioisotopes of albumin (e.g. \(^{131}\)I-albumin) or Evans blue dye, also called T-1824, which binds tightly to albumin (the small amount of albumin that enters the interstitial fluid can usually be neglected in dilution studies). Another method for estimating plasma volume first determines the blood volume by dilution using labelled erythrocytes (e.g. \(^{51}\)Cr-erythrocytes). The plasma volume can then be calculated as follows:

\[
\text{Plasma volume} = \text{Blood volume} (1 - \text{Hct}) \tag{Eq.10.3}
\]

where Hct is the haematocrit. Since the haematocrit measured from a peripheral vein slightly overestimates the actual haematocrit (because the haematocrit in small capillaries is slightly less than that in larger vessels), the labelled erythrocyte method slightly underestimates the plasma volume. A method of estimating percentage changes in volumes of plasma and of red cells was developed by Dill & Costill (1974), using measurement of concentration of haemoglobin in blood and percentage of red cells in blood before and after dehydration.

**ICF and Interstitial Fluid:** No markers are available that distribute exclusively in the ICF and interstitial compartments, so dilution methods cannot be used to measure the volumes of these compartments. However, once the volumes of the TBW and ECF have been estimated by dilution, the volume of ICF can be calculated as follows:
ICF = TBW - ECF  

(Eq. 10.4)

Since different markers are used to estimate ECF volume, the ICF values calculated using Equation 10.4 will also vary, so a distinction between methods used is important. Due to this, the approximation that ICF contains about two-thirds of TBW is often used for clinical purposes. The volume of interstitial fluid can be calculated from the ECF and plasma volumes:

Interstitial fluid = ECF - plasma  

(Eq. 10.5)

When estimating ECF using dilution methods, in addition to interstitial fluids and plasma, variable amounts of dense connective tissue and transcellular fluid are also included. Therefore, the volume of interstitial fluid calculated using Equation 10.5 slightly overestimates the true volume.

Another technique that may be used to measure the volume of body water compartments is bio-electrical impedance, which is discussed at length in Chapter 5.

10.2.3 Composition of the Body Fluids

Extracellular Fluid: The two major compartments of the ECF, plasma and interstitial fluid, have very similar compositions, with Na⁺ as the predominant cation and Cl⁻ and HCO₃⁻ as the predominant anions. However, an important difference between plasma and interstitial fluid is the larger concentration of proteins in plasma. This difference exists because the capillary endothelium is freely permeable to water and small solutes, such as inorganic ions, glucose and urea, but has limited permeability to larger solutes, such as large proteins and lipids. Given the high permeability of the capillary endothelium to small solutes, it might be expected that the concentrations of solutes in plasma and interstitial fluid would be identical. Plasma concentrations are typically measured in clinical settings as meq / litre of plasma volume or mmol / litre of plasma volume. However, to compare plasma and interstitial fluid concentrations, the plasma concentrations must be corrected to account for the significant fraction of the plasma volume occupied by proteins and lipids. The small solutes that can diffuse across the capillary endothelium are part of the aqueous phase of plasma, which normally occupies about 93% of the total plasma volume; the remaining 7% is occupied by plasma proteins and lipids. Therefore, plasma concentrations must be
expressed as meq / litre of plasma water or mmol / litre of plasma water in order to be compared to interstitial fluid concentrations. Values expressed as meq / litre or mmol / litre of plasma volume can be converted to plasma water values by dividing by 0.93 (Table 10.4). Once such conversions are made, the plasma and interstitial fluid concentrations of small non-electrolytes are identical, but small electrolytes have slightly different concentrations in plasma and interstitial fluid. Such differences can be attributed to the Gibbs-Donnan Effect.

**Table 10.4: Approximate concentrations of solutes in body fluids**

<table>
<thead>
<tr>
<th></th>
<th>Plasma meq / litre</th>
<th>Plasma water meq / litre H2O</th>
<th>Interstitial fluid meq / litre H2O</th>
<th>Intracellular fluid meq / litre H2O</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na⁺</td>
<td>142</td>
<td>153</td>
<td>145</td>
<td>10</td>
</tr>
<tr>
<td>K⁺</td>
<td>4</td>
<td>4.3</td>
<td>4.1</td>
<td>159</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>2.5</td>
<td>2.7</td>
<td>2.4</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>1</td>
<td>1.1</td>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td>Total</td>
<td>149.5</td>
<td>161.1</td>
<td>152.5</td>
<td>209</td>
</tr>
<tr>
<td><strong>Anions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cl⁻</td>
<td>104</td>
<td>112</td>
<td>117</td>
<td>3</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>24</td>
<td>25.8</td>
<td>27.1</td>
<td>7</td>
</tr>
<tr>
<td>Proteins</td>
<td>14</td>
<td>15.1</td>
<td>&lt;0.1</td>
<td>45</td>
</tr>
<tr>
<td>Other</td>
<td>7.5</td>
<td>8.2</td>
<td>8.4</td>
<td>154</td>
</tr>
<tr>
<td>Total</td>
<td>149.5</td>
<td>161.1</td>
<td>152.5</td>
<td>209</td>
</tr>
<tr>
<td><strong>Non-electrolytes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glucose</td>
<td>4.7</td>
<td>5.0</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>Urea</td>
<td>5.6</td>
<td>6.0</td>
<td>6.0</td>
<td></td>
</tr>
</tbody>
</table>

* skeletal muscle

From Laiken & Fanestil, 1990a

**Gibbs-Donnan Effect:** At equilibrium the distribution of Na⁺ and Cl⁻ between the plasma and interstitial fluid compartments is given by the Gibbs-Donnan relationship:

\[ P_{Na} \cdot P_{Cl} = ISF_{Na} \cdot ISF_{Cl} \]  

(Eq. 10.6)

where P and ISF represent the concentrations of the ions in the plasma and interstitial fluid compartments respectively. Due to the presence of negatively charged proteins in the plasma and not the interstitial fluid, there will be additional Na⁺ ions present in the plasma to act as counterions. Na⁺ then diffuses from the plasma to the interstitial...
fluid along its concentration gradient, accompanied by Cl\(^-\) to maintain electrical neutrality. However, this migration will increase the concentration of Cl\(^-\) in the interstitial fluid compartment, thereby generating a concentration gradient that opposes the further diffusion of Cl\(^-\) from the plasma to the interstitial fluid. Therefore, because of the anionic protein in the plasma compartment, the equilibrium state between the two compartments is characterised by three important features: 1) the small diffusible ions (Na\(^+\), Cl\(^-\)) do not have equal concentrations in the two compartments, the cation (Na\(^+\)) concentration being slightly higher in the protein-containing plasma and the anion (Cl\(^-\)) concentration being slightly higher in the interstitial fluid; 2) the total concentration of the equivalents of charge is greater in the protein-containing plasma; and 3) despite the differences in ion concentrations and in the total concentration of equivalents of charge, electrical neutrality is maintained within each compartment.

Having discussed the differences in the composition of plasma and interstitial fluid, these differences are actually sufficiently small that for most clinical purposes the electrolyte concentrations in plasma can be assumed to be representative of those in the ECF in general. Similarly, while the distinction between plasma concentrations expressed in terms of plasma volume or plasma water is important for a precise comparison of plasma and interstitial fluid compositions, and for consideration of the Gibbs-Donnan effect, here, the concentrations as measured by most clinical laboratories (meq / litre or mmol / litre of plasma volume) will be used.

**Intracellular Fluid:** In contrast to the very similar composition of the plasma and interstitial fluid compartments, the composition of the ECF differs considerably from that of the ICF. Each cell is surrounded by a highly selective plasma membrane that permits passage of certain materials while excluding others. Movement through the membrane carrier occurs by both passive and active means and may be highly discriminating. In contrast to the ECF, ICF contains relatively low concentrations of Na\(^+\), Cl\(^-\) and HCO\(_3^-\). Instead, the predominant cation in ICF is K\(^+\), while the predominant anions are organic phosphates (e.g. ATP) and proteins. Such differences between ICF and ECF are due to: 1) the unequal distribution of Na\(^+\) and K\(^+\) and their attendant anions as a result of the action of the membrane-bound Na\(^+\)-K\(^+\) ATPase pump that is present in all cells. This pump actively transports Na\(^+\) out of and K\(^+\) into
cells; This unequal distribution of $\text{Na}^+$ and $\text{K}^+$, coupled with differences in membrane permeability to these ions, is responsible for the electrical properties of cells; and 2) the presence of cellular proteins and organic phosphates that are unable to permeate the enveloping membranes to leave the cells, resulting in the establishment of a Gibbs-Donnan equilibrium across the cell membrane.

Except for the extremely small, electrically imbalanced proportion of the total extracellular and intracellular ions that are involved in membrane potential, the majority of the ECF and ICF ions are electrically balanced. Although all cells' plasma membranes display selective permeability, all cells are freely permeable to water. The movement of water between the plasma and interstitial fluid across capillary walls is governed by relative imbalances in capillary blood pressure and colloid osmotic pressure. In contrast, the net transfer of water between the interstitial fluid and the ICF across the cellular membranes occurs as a result of osmotic effects alone. The hydrostatic pressures of the interstitial fluid and the ICF are both extremely low and fairly constant.

10.2.4 Osmolality of the Body Fluids

When studying topics that involve fluid and electrolyte balance, the osmolality of the body fluids and how this affects the distribution of body water between fluid compartments must be considered. Despite the differences in composition, Figure 10.1 illustrates that plasma, interstitial fluid and intracellular fluid have almost identical osmolalities, that is approximately 290 mosmol/kg $\text{H}_2\text{O}$. This is due to the fact that the capillary endothelium and most cell membranes are freely permeable to water, allowing the three compartments to be iso-osmotic. The main factor that affects the distribution of water between the ECF and ICF compartments is the number of osmotically active solute particles in each compartment. The osmolality of a fluid is a measure of the concentration of the individual solute particles dissolved in it. Each individual solute particle exerts the same osmotic effect, regardless of its size or molecular weight. Therefore, osmolality is determined by the number of solute particles within a given volume of fluid, not by the mass of the solute particles. The higher the osmolality, the higher the concentration of solutes or the lower the concentration of water. Water tends to move by osmosis from an area of lower solute
(higher water) concentration to an area of higher solute (lower water) concentration down its own concentration gradient. Therefore, the fact that plasma, interstitial fluid and ICF contain different total concentrations of equivalents of charge does not affect the iso-osmolality of these body fluids.

The principle of iso-osmolality should only be applied to the major body fluids, as a few minor volumes of fluid have osmolalities that differ significantly from 290 mosmol / kg H$_2$O, such as the peritubular interstitial fluid in the renal medulla, which can have an osmolality as high as 1200 mosmol / kg H$_2$O, and certain transcellular fluids, in particular urine, which can vary from 70 to 1200 mosmol / kg H$_2$O.

![Figure 10.1: Osmotic composition of the major body fluids (adapted from Beck, 1971)](image-url)
10.2.5 Plasma Osmolality

The osmolality of the major body fluids can be studied by analysing the osmolality of plasma, due to the iso-osmolality principle discussed earlier. This system is described by Best & Taylor (1990) as follows: the plasma osmolality can be estimated as the sum of the contributions from electrolytes, glucose and urea:

\[ P_{\text{osm}} = \text{osmolality of electrolytes} + \text{osmolality of glucose} + \text{osmolality of urea} \]  \hspace{1cm} (Eq. 10.7)

where it can be assumed that the osmotic contribution of glucose and urea remain constant at approximately 10 mosmol / H2O. Since Na\(^+\) and its attendant anions represent the major electrolytes in plasma, it can be assumed that:

\[ \text{Osmolality of electrolytes} \approx \text{osmolality of (Na}^+ + \text{attendant ions)} \] \hspace{1cm} (Eq. 10.8)

In addition, it is also assumed that each Na\(^+\) ion is paired with a univalent anion, as follows:

\[ \text{Osmolality of electrolytes (mosmol / kg H}_2\text{O)} \approx 2P_{\text{Na}} \,(\text{mmol / litre}) \] \hspace{1cm} (Eq. 10.9)

Therefore, since glucose and urea contributions normally account for about 10 mosmol / kg H2O, plasma osmolality can be expressed as:

\[ P_{\text{osm}} \,(\text{mosmol / kg H}_2\text{O)} \approx 2P_{\text{Na}} \,(\text{mmol / litre}) + 10 \] \hspace{1cm} (Eq. 10.10)

However, while \(P_{\text{Na}}\) can be a good index of \(P_{\text{osm}}\), \(P_{\text{Na}}\) is not a good index of either the total amount of osmotically active solute in the body or the TBW (Edelman et al, 1958). The following is a set of examples illustrating this by Laiken & Fanestil (1990a), involving changes in body solute or TBW. Figure 10.2A illustrates the volumes and osmolality of the ECF and ICF in a normal, young, adult male, weighing 60kg. Using the clinical approximations discussed earlier, TBW is 36 litres (60% of body weight), ECF is 12 litres (about one-third of TBW) and ICF is 24 litres (about two-thirds of TBW). If \(P_{\text{osm}}\), and hence the osmolality of the major body fluids, is 290 mosmol / kg H2O, then the amount of osmotically active solute in the TBW, ECF and ICF can be calculated as follows:
TBW_{osm} = \text{Total body osmotically active solute}

\begin{align*}
\text{TBW} = \text{TBW}_{osm} \times \text{TBW} \\
= 290 \text{ mosmol/kg H}_2\text{O} \times 36 \text{ litres} \\
= 10,440 \text{ mosmol}
\end{align*}

\text{ECF}_{osm} = \text{Extracellular osmotically active solute}

\begin{align*}
\text{ECF} = \text{ECF}_{osm} \times \text{ECF} \\
= 290 \text{ mosmol/kg H}_2\text{O} \times 12 \text{ litres} \\
= 3,540 \text{ mosmol}
\end{align*}

\text{Figure 10.2: Effects of changes in body solute or TBW on osmolality of body fluids and on distribution of water between ECF and ICF (from Best & Taylor, 1990)}
ICF = Intracellular osmotically active solute

ICF

Intracellular osmotically active solute = ICF \times ICF

= 290 \text{mosmol / kg H}_2\text{O} \times 24 \text{litres}

= 6960 \text{mosmol}

Figure 10.2B illustrates the changes in the volumes and osmolality in the ECF and ICF that would result from the sudden loss of 360 mosmol of Na\(^+\) and 360 mosmol of anions without changing the TBW. Since Na\(^+\) is predominantly an extracellular ion, it can be assumed that this 720 mosmol of solute is lost exclusively from the ECF. The sudden loss of solute from the ECF without any change in the TBW reduces the osmolality of the ECF. However, this decrease in the osmolality of the ECF can only be transient, since water will move from the ECF to the ICF until the osmolalities of all major body fluids are equal. Therefore, although the solute is lost primarily from the ECF, the net result is a decrease in the osmolality of all major body fluids. Following this redistribution of water, the new osmolality of the body fluids can be calculated by substituting the new value for the total body osmotically active solute into Eq. 10.11:

\[
\text{TBW}_{\text{omn}} = 10.440 \text{mosmol} - 720 \text{mosmol} = 270 \text{mosmol / kg H}_2\text{O}
\]

The new volume of the ECF after the redistribution of water can be calculated by substituting the new values for extracellular osmotically active solute and osmolality into Eq. 10.12:

\[
\text{ECF} = \frac{3480 \text{mosmol} - 720 \text{mosmol}}{270 \text{mosmol / kg H}_2\text{O}} = 10.2 \text{litres}
\]

In other words, the loss of 720 mosmol of Na\(^+\) and attendant anions from the ECF results in the shift of approximately 1.8 litres of the original 12 litres of ECF to the ICF.

Figure 10.2C shows that changes in the volumes and osmolality of the ECF and ICF that would result from the sudden loss of 360 mosmol of K\(^+\) and 360 mosmol of
anions, again without changing the TBW. Since K\textsuperscript+ is predominantly an intracellular ion, it can be assumed that this 720 mosmol of solute is lost exclusively from the ICF. The sudden loss of solute from the ICF without any change in the TBW reduces the osmolality of the ICF. However, this decrease in the osmolality of the ICF can only be transient, since water will move from the ICF to the ECF until the osmolalities of all major body fluids are equal. Therefore, although the solute is lost primarily from the ICF, the net result is a decrease in the osmolality of all major body fluids. Following this redistribution of water, the new osmolality of the body fluids can be calculated by substituting the new value for the total body osmotically active solute into \textit{Eq. 10.11}:

\[
TBW_{\text{new}} = 10,440 \text{ mosmol} - 720 \text{ mosmol} \\
\text{36 litres} = 270 \text{ mosmol/kg H}_2\text{O}
\]

It should be noted that the decrease in osmolality is the same as that resulting from the loss of 720 mosmol of solute from the ECF (Fig. 213). The new volume of the ICF after the redistribution of water can be calculated by substituting the new values for intracellular osmotically active solute and osmolality into \textit{Eq. 10.13}:

\[
ICF = 6960 \text{ mosmol} - 720 \text{ mosmol} \\
\text{270 mosmol/kg H}_2\text{O} = 23.1 \text{ litres}
\]

In other words, the loss of 720 mosmol of K\textsuperscript+ and attendant anions from the ICF results in the shift of approximately 0.9 litres of the original 24 litres of ICF to the ECF.

Figure 10.213 illustrates the changes in the volumes and osmolality of the ECF and ICF that would result from the sudden addition of 2.7 litres of distilled water to the ECF with no change in total body osmotically active solute. This addition of water reduces the osmolality of the ECF. However, this decrease in ECF osmolality can only be transient, since water will move from the ECF to the ICF until the osmolalities of all major body fluids are equal. Following this redistribution of water (assuming that none of the water is excreted), the new osmolality of the body fluids can be calculated by substituting the new value for TBW into \textit{Eq. 10.11}:
The new volumes of the ECF and ICF can be calculated by substituting the new value for body fluid osmolality into Eqs. 10.12 and 10.13 (It should be noted that the quantity of osmotically active solute in each compartment does not change):

\[
\text{ECF} = \frac{3480 \text{ mosmol}}{270 \text{ mosmol/kg H}_2\text{O}} = 12.9 \text{ litres}
\]

\[
\text{ICF} = \frac{6960 \text{ mosmol}}{270 \text{ mosmol/kg H}_2\text{O}} = 25.8 \text{ litres}
\]

Therefore, approximately one-third of the added 2.7 litres of water distributes into the ECF, while two-thirds distributes into the ICF.

From each of the three examples of changes in body solute and water illustrated in Figure 10.2, the osmolality of the major body fluids decreases from 290 to 270 mosmol / kg H₂O. Furthermore, if it is assumed that the osmotic contribution of glucose and urea remains constant at approximately 10 mosmol / kg H₂O, then from Eq. 10.10, it can be seen that PNa decreases from 140 to 130 mmol / litre in each case. There are several other reasons for being able to predict this result. Since the major body fluids are iso-osmotic, Eq. 11 can be used to calculate P_{osm} as well as TBW_{osm}:

\[
P_{osm} = \frac{\text{Total body osmotically active solute}}{\text{TBW}} \quad (\text{Eq. 10.14})
\]

Na⁺ and K⁺ and their attendant anions are the major osmotically active solutes in the body fluids. In addition, the osmotically active Na⁺ and K⁺ in the body fluids are closely approximated by the exchangeable Na⁺ (Na⁺ₑ) and K⁺ (K⁺ₑ) as follows (the multiplier 2 accounts for the osmotic contributions of the attendant anions):
From Eq. 10, $P_{\text{osm}}$ is also approximated by $2P_{\text{Na}}$, if the osmotic contributions of glucose and urea are neglected, so substituting this approximation into Eq. 10.15 gives:

$$P_{\text{Na}} \approx \frac{Na^+}{TBW} + \frac{K^+}{TBW}$$

(Eq. 10.16)

Therefore, from these considerations it can be seen that a decrease in body $Na^+$, a decrease in body $K^+$, or an increase in TBW could result in a similar change in $P_{\text{Na}}$. The examples illustrated in Figure 10.2 and also Eq. 10.16 emphasise an important point about the use of $P_{\text{Na}}$ as an index of $P_{\text{osm}}$ and hence body fluid osmolality: $P_{\text{Na}}$ does not, by itself, give any information about either the total amount of osmotically active solute in the body or the TBW. Eq. 10.16 can be useful in analysing the changes in body solute or TBW that can occur, for example, during sweating in a hot environment without water intake. This process would result in a decrease in both $Na^+$ and TBW, but since sweat is ordinarily hypotonic relative to plasma (Sawka, 1996), the percentage decrease in TBW will be greater than the percentage decrease in $Na^+$. Therefore, $P_{\text{Na}}$ will increase in spite of the decrease in $Na^+$ (Eq. 10.16).

10.3 Regulation of the body fluids

10.3.1 The Balance Concept

Input of water and solutes must equal output if balance of normal volume and osmolality of the body fluids is to be maintained. The cells of complex multicellular organisms are able to survive only within a very narrow range of composition of the ECF, the internal fluid environment that bathes them. The quantity of any particular substance in the ECF is considered to be a readily available internal pool. Water is the only solvent of concern in this matter, but many different solutes contribute to the osmolality of the body fluids. As the major extracellular solute is $Na^+$, along with its attendant anions, the regulation of the volume and osmolality of the ECF depends almost entirely on the regulation of water and $Na^+$. Such balances of water and $Na^+$ in the ECF will influence the volume and osmolality of the ICF, since cell membranes
are permeable to water. More of a particular substance may be added to the ECF pool either by being transferred in from the external environment (most commonly by ingestion) or by being metabolically produced within the body. Substances may be removed from the body by excretion to the outside or by consumption in a metabolic reaction. If the quantity of a substance is to remain stable within the body, its input by means of ingestion or metabolic production must be balanced by an equal output by means of excretion or consumption. This relationship, or balance concept, is extremely important in the maintenance of homeostasis.

When total body input of a particular substance equals its total body output, a stable balance exists. When the gains via input for a substance exceed its losses via output, a positive balance exists. The result is an increase in the total amount of the substance in the body. In contrast, when the losses for a substance exceed its gains, a negative balance exists and the total amount of the substance in the body decreases.

Not all input and output pathways are applicable for every body fluid constituent:

1. In the case of an electrolyte such as salt, stability of plasma NaCl concentration depends entirely on a balance between salt ingestion versus salt excretion. Salt is not synthesised or consumed by the body, and it lacks storage sites outside the ECF.

2. For water (H2O) and free hydrogen ions (H\(^+\)), all input and output pathways to and from the ECF pool are possible. The amount of either substance in the ECF can be altered both by exchange between the ECF and external environment and by exchange between the ECF and the cells.

Changing the magnitude of any of the input or output pathways for a given substance can alter its plasma concentration. In order to maintain homeostasis, any change in input must be balanced by a corresponding change in output (eg. increased salt intake must be matched by a corresponding increase in the salt output in the urine), and conversely, increased losses must be compensated for by increased intake. Thus, maintenance of a stable balance necessitates control. However, not all input and output pathways are regulated to maintain balance. Generally, input of various plasma constituents is poorly controlled or not controlled at all. We frequently ingest
water and salt, for example, not because we need them, but because we want them, so the intake of water and salt is highly variable. Likewise, H\(^+\) is uncontrollably generated internally and added to the body fluids. Water, salt and H\(^+\) can also be lost to the external environment to varying degrees through the digestive tract (vomiting), skin (sweating), and elsewhere (water vapour loss from the respiratory passages) without regard for water, salt or H\(^+\) balance in the body. Compensatory adjustments in the urinary excretion of these substances are responsible for maintaining the body fluids' volume and salt and acid composition within the extremely narrow homeostatic range compatible with life despite wide variations in input and unregulated losses of these plasma constituents.

10.3.2 Water balance

**Water intake**

The sources of input and output of water are varied (more varied, for example, than for salt). The skin and other epithelial surfaces, such as the lining of the digestive tract, the respiratory tract, and urinary tract, act as barriers between the body fluids and the external environment. Water can be added to the body fluids via three sources: the water content of food; the water generated during the oxidation of food; and the water consumed as liquid. *Table 10.5* shows the typical daily water balance for an average 75kg man. The amount of water in food can vary widely: meat is 75% water because it is animal muscle (muscles consist of about 75% water) and fruit and vegetables consist of 60-90% water, whereas many processed, packaged foods contain little or no water. The amount of water in food may become important if an individual is exposed to heat and loses vital body water through sweating. The second source of water input is metabolically produced water. Chemical reactions in the cells convert food and oxygen into energy, producing carbon dioxide and water in the process. This metabolic water, which is produced during cellular metabolism and released into the ECF, averages about 350 ml/day. Neither the water obtained from food, nor the water generated during the oxidation of food is an important factor in the regulation of water input.
Table 10.5: Daily water balance for an average 75kg man resting in a moderate environment (adapted from McCardle et al, 1991)

<table>
<thead>
<tr>
<th>Source</th>
<th>Volume (ml)</th>
<th>Source</th>
<th>Volume (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluids</td>
<td>1200</td>
<td>Urine</td>
<td>1500</td>
</tr>
<tr>
<td>Solid food</td>
<td>1000</td>
<td>Faeces</td>
<td>100</td>
</tr>
<tr>
<td>Metabolism</td>
<td>350</td>
<td>Insensible loss</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td>Total 2550</td>
<td>Sweat</td>
<td>250</td>
</tr>
</tbody>
</table>

Therefore, water input is almost solely regulated by the third source, water consumed as liquid. The changes in volume consumed average 1-2 litres per day, but range from less than 1 litre per day to more than 20 litres per day. For example, the sensation of thirst arises when large amounts of water are lost through sweating and then liquid consumption increases. However, during normal conditions, an individual’s desire to drink is driven more by habit and sociological factors than by the need to regulate water balance or by thirst. Thus, even though water intake is critical in maintaining fluid balance, it is not precisely controlled in humans: there may be excess fluid consumption, for example, when an individual is not thirsty but on a coffee break; or a person may not consume enough fluid despite the fact that they are thirsty, for example, if protective clothing is worn, it may be particularly inconvenient to halt work and undress in order to drink. With water intake being inadequately regulated and indeed even contributing to water imbalances in the body, the primary factor involved in maintaining water balance is urinary output regulated by the kidneys.

**Water output**

There are four routes through which water can be lost from the body, the first being the primary regulator: urine, faeces, insensible loss and sweat. Change in the volume of urine is the most important mechanism in the regulation of water output. An average of approximately 1500 ml of urine is produced per day, but this can range from less than 1 litre / day to more than 20 litres / day. Urine is the primary regulator of body water output because the body is unable to prevent loss via the three remaining routes; thus, faeces, insensible loss and sweat are termed ‘obligatory losses’. Faecal loss of water in normal man is only about 100 ml every day. During the process of faecal formation in the large intestine, most of the water is absorbed out
of the digestive tract lumen into the blood, thereby conserving fluid and solidifying
the digestive tract’s contents for elimination. Water loss by this route may exceed 5
litres / day in diarrhoeal diseases such as cholera. Insensible loss occurs from the
lungs and non-sweating skin and approximately 700 ml of water is lost daily in this
way without a person’s awareness. During respiration, inspired air becomes saturated
with water within the airways and this water is lost when the moistened air is
subsequently expired. The other avenue of insensible loss is the continual loss of
water from the skin even in the absence of sweating (the water of transpiration).
Water molecules diffuse through the skin cells and evaporate, but the skin’s
keratinized exterior layer protects against much greater water loss.

The loss of water from the skin by means of sweating represents the final avenue of
water output and is termed sensible loss. It is produced by the sweat glands in
response to thermal stress. An individual at rest in a cool environment may lose less
than 200 ml of water per day through sweating. This figure can rise substantially, to
as much as 8-10 litres per day, if the environmental temperature, humidity and / or
degree of physical activity increase; acclimatisation may cause further increases in
sweat production (discussed in detail in Chapter 2).

Control of water balance
In everyday conditions, body water content remains remarkably consistent. It is
suggested that since daily fluctuations in body weight may be no more than 150
grams, it is likely that daily variations in the amount of body water are no greater
(Beck, 1971). This means that for a 70kg man, body water content fluctuates only
0.036% (that is, 150 / 42,000 for a 70 kg adult whose body water constitutes 60% of
his total body weight). Of the many sources of water input and output, only two can
be regulated to maintain water balance: thirst influences the amount of fluid ingested,
and the kidneys can adjust the magnitude of urine formation. Some of the other
routes of input and output are regulated, although not for the purpose of maintaining
water balance: food intake is subject to regulation to maintain energy balance,
whereas control of sweating is important in the maintenance of body temperature.
Metabolic production and insensible losses are completely unregulated.
Changes in the volume of liquid ingested and urine produced are controlled by thirst and the ADH (secreted by the posterior pituitary) plasma level respectively. Both thirst and the plasma level of ADH are controlled by centres in the hypothalamus, which are stimulated by two changes in the plasma: increased osmolality and decreased volume.

*Increased plasma osmolality* - The hypothalamic osmoreceptors that monitor the ECF’s osmolality provide the predominant excitatory input to both the thirst centre and the ADH-secreting cells. The osmoreceptors respond to increases in plasma osmolality produced by either a deficit of total body water or a predominance of extracellular solutes, causing water to shift from the intracellular to the extracellular compartment. When a negative water balance exists, as manifested by an increase in ECF osmolality, thirst and ADH secretion are both stimulated. ADH promotes water reabsorption and hence water conservation for the body by increasing the permeability of the distal portions of the renal tubules to water.

*Decreased plasma volume* - The thirst centre and ADH secreting cells are both influenced by changes in ECF volume mediated by input from baroreceptors. The baroreceptors are located in both the low-pressure regions (atria) and the high-pressure regions (carotid sinus and aortic arch) of the circulation (Zerbe & Robertson, 1987), and they monitor venous pressure as a reflection of ECF volume. A volume deficit inhibits the firing of these receptors, which causes a reflex stimulation of both thirst and ADH (thus decreasing urinary output), whereas a volume excess suppresses thirst and ADH secretion.

Since the osmoreceptors are extremely sensitive to small changes in plasma osmolality, thirst and ADH secretion are normally under their control. Indeed, even when the plasma osmolality changes by as little as 1%, there are significant changes in ADH secretion. However, as much as a 10% change in plasma volume may be necessary before significant changes in ADH secretion take place (Robertson et al, 1976). Therefore, only in extreme situations, such as severe dehydration or haemorrhage, do changes in plasma volume primarily affect thirst and ADH secretion. Although the osmoreceptors are more sensitive than the baroreceptors (volume receptors), the stimulation of the latter results in a greater response. For example, a
very high plasma volume will result in the suppression of ADH secretion, even when the plasma is hypertonic, and likewise, thirst and ADH are still stimulated at a low plasma osmolality when the plasma volume is very low. This can be summarised as 'volume overrides tonicity' (Robertson et al, 1976).

Although the major stimulus for both thirst and increased ADH secretion is an increase in ECF osmolality, other factors also affect these water-regulating mechanisms. When the renin-angiotensin-aldosterone mechanism is activated to restore intravascular and extracellular fluid volumes by conserving sodium, urinary output is reduced as water is osmotically conserved. Angiotensin II is synthesised by this process, and in addition to stimulating aldosterone secretion, it acts directly on the brain to give rise to the urge to drink while it simultaneously stimulates ADH to enhance renal water reabsorption. The resultant increased water intake and decreased urinary output help to correct the reduction in ECF volume that triggered the renin-angiotensin-aldosterone system. Several factors affect ADH secretion but not thirst. Stress-related inputs, such as pain, fear and trauma, that have nothing directly to do with maintaining water balance, stimulate the production of ADH. In fact, water retention as a result of the inappropriate secretion of ADH can bring about a hypotonic water imbalance. Conversely, alcohol inhibits ADH secretion and can lead to ECF hypertonicity by promoting excess free water excretion. One stimulus that promotes thirst but not ADH secretion is a direct effect of dryness of the mouth. Nerve endings in the mouth are stimulated by dryness, which causes an intense sensation of thirst that can often be relieved merely by moistening the mouth, even though no water is actually ingested. The regulation of water input and output by thirst, ADH secretion and the renin-angiotensin-aldosterone mechanism in order to restore plasma osmolality and volume after an instance of acute dehydration is summarised in Figure 10.3.
10.3.3 Sodium balance

Sodium intake

The only avenue for sodium input is ingestion (food and water), which typically is well in excess of the body’s need for replacement of obligatory salt losses. The average dietary intake of sodium in the UK is around 4 grams per day (Gregory et al, 1990), or 3.6 grams per day, with a range of 1.2 - 7.2 grams per day (Department of Health, 1994). A half gram of salt per day is adequate to replace the small amounts of salt usually lost in the faeces and sweat. Since we typically consume salt in excess of our needs (Table 10.6), it is obvious that salt intake in humans is not well-controlled. Humans generally have an indulgent rather than a regulatory appetite for salt, so that man’s heavy salt consumption is more a matter of acquired taste.
**Table 10.6: Daily sodium balance**

<table>
<thead>
<tr>
<th>Avenue</th>
<th>Amount (g/day)</th>
<th>Avenue</th>
<th>Amount (g/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingestion</td>
<td>1.2 - 7.2</td>
<td>Obligatory loss in sweat and faeces</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Controlled excretion in urine</td>
<td>0.7 - 6.7</td>
</tr>
<tr>
<td>Total input</td>
<td>1.2 - 7.2</td>
<td>Total output</td>
<td>1.2 - 7.2</td>
</tr>
</tbody>
</table>

From Department of Health (1994)

**Sodium output**

Maintenance of sodium balance requires that inputs must equal outputs, so the excess ingested salt must be excreted in the urine. The three avenues for sodium output are obligatory loss of sodium in sweat and faeces and controlled excretion of sodium in the urine (Table 10.6). Sodium loss in sweat is only partially regulated. The total amount of sweat produced is unrelated to sodium balance, being determined instead by factors that control body temperature. However, the amount of sodium lost in sweat depends both on the volume of sweat and the degree of heat acclimatisation of the individual; the concentration of sodium in sweat decreases with acclimatisation, which can take place over several days. Therefore, sodium loss in sweat can range from negligible in a person at rest in a cool environment to 1.2 grams per litre (Robinson & Robinson, 1954) for a non-acclimatised person working or exercising in the heat. The small salt loss in the faeces is not subject to control. Except when sweating heavily or during diarrhoea, the body normally uncontrollably loses about 0.5 grams of sodium per day. This is actually the only sodium that normally needs to be replaced by salt intake. Therefore, sodium output, like water output, is regulated primarily by changes in the amount of sodium excreted in the urine. The kidneys precisely excrete the excess sodium in the urine in order to maintain salt balance. In the example in Table 10.6, 1.2 - 7.2 grams of sodium is eliminated in the urine per day so that total sodium output equals exactly sodium input. By regulating the rate of urinary salt excretion (that is, regulating the rate of sodium excretion, with chloride following along), the kidneys normally keep the total sodium mass in the ECF constant despite any notable changes in dietary intake of salt or unusual losses through sweating, diarrhoea, or other means.
Regulation of sodium balance
Since there is no means of regulating sodium input, balance must be achieved by regulating sodium output in the urine according to input. As a reflection of keeping the total sodium mass in the ECF constant, the ECF volume in turn is maintained within the narrowly prescribed limits essential for circulatory function. The kidneys control the amount of sodium excreted by two major regulatory processes: changes in the glomerular filtration rate (GFR) and aldosterone.

Changes in GFR
Renal plasma flow (RPF) is the most important regulator of GFR. Changes in sodium intake can affect both RPF and net filtration pressure, and hence GFR. The GFR does not respond directly to changes in sodium intake; rather, adjustments in the amount of sodium filtered are accomplished as part of the general blood pressure regulating reflexes. Changes in sodium load in the body are monitored indirectly through the effect that sodium ultimately has on blood pressure via its role in determining the ECF volume. Therefore, it is the baroreceptors that monitor fluctuations in blood pressure and are responsible for bringing about adjustments in the amount of sodium filtered and eventually excreted. For example, if there was an increase in sodium intake, there would be an increase in plasma osmolality (as sodium is primarily an extracellular solute), which would stimulate the osmoreceptors. The resulting stimulation of thirst and ADH secretion would create a subsequent elevation in ECF volume and arterial blood pressure. This would be countered by an increase in both RPF and net filtration pressure, that in turn lead to an increase in GFR. The greater filtered load of sodium results in enhanced salt and fluid excretion. The extra elimination of salt and fluid that otherwise would have been conserved helps relieve the expanded plasma volume. This process is illustrated in Figure 10.4. Conversely, with a reduction in sodium intake, the afferent arterioles that supply the renal glomeruli are constricted as part of the generalised vasoconstriction aimed at elevating a reduction in blood pressure. As a result of reduced blood flow into the glomeruli, GFR decreases, and, accordingly, the amount of sodium and accompanying fluid that are filtered decreases. Consequently, secretion of salt and fluid is diminished and this aids in minimising the reduction in fluid volume and contributes to long term restitution of blood pressure.
Figure 10.4: The pathway by which sodium balance could be restored by an increase in GFR, following an increase in sodium intake

However, changes in GFR are of minor importance in the regulation of sodium, due to three reasons: autoregulation (the maintenance of a constant supply to the kidneys, via the RPF and GFR, despite large changes in mean systemic arterial pressure); tubuloglomerular feedback (the regulation of glomerular blood flow and filtration by...
the arterioles as a response to the signals sent from the fluid delivered to the distal nephron); and glomerulotubular balance (the load dependant reabsorption of sodium, which comes about because the amount of sodium reabsorbed by the proximal tubule, loop of Henle and distal nephron varies directly with the load of sodium delivered to that region). Therefore, the majority of sodium regulation must be carried out by aldosterone.

**Aldosterone**

The secretion of aldosterone, a steroid hormone, by the adrenal cortex is stimulated by several factors, three of which are decreased plasma sodium, increased plasma angiotensin II and decreased atrial natriuretic factor (ANF). Increased plasma levels of aldosterone stimulate sodium reabsorption in the collecting duct, which brings about a reduction in sodium excretion. Since decreases in plasma sodium have a relatively weak stimulus on the production of aldosterone, and changes in sodium intake have minimal effects on plasma sodium (since extra sodium intake only produces a transient increase in plasma volume, until plasma tonicity causes the osmoreceptors to stimulate thirst and ADH secretion), the dominant factors controlling the extent of sodium reabsorption in the distal tubule are the powerful renin-angiotensin-aldosterone system, which brings about angiotensin II, and ANF. Angiotensin II is formed as follows (the enzyme renin that catalyses the first step of the reaction is secreted into the plasma by the granular cells of the juxtaglomerular (JG) apparatus in the kidney):

\[
\text{renin} \quad \text{converting enzyme} \\
\text{Angiotensin} \rightarrow \text{angiotensin I} \rightarrow \text{angiotensin II}
\]

ANF is a hormone synthesised in and secreted from atrial muscle cells in response to stretch. An example of this combined regulatory system following excess salt intake would result in increased plasma volume and blood pressure, which in turn would cause an increase in ANF secretion and a decrease in renin secretion, and hence angiotensin II. This latter phase results in a decline in aldosterone secretion and a subsequent reduction in sodium reabsorption. The resultant loss of extra salt and its accompanying water help alleviate the salt excess, expanded plasma volume and elevated blood pressure. The converse also applies: renin, by means of angiotensin activation, brings about secretion of aldosterone. Aldosterone, in turn, stimulates the
reabsorption of sodium from the distal portion of the tubule. As more sodium is reabsorbed, less sodium is excreted. The conserved sodium and the water that osmotically accompanies it help restore the fallen blood pressure to normal. *Figure 10.5* illustrates the changes in angiotensin II production and ANF secretion that may come about as a result of increased sodium intake. Therefore, the regulation of sodium excretion by aldosterone occurs as a result of changes in plasma volume, which come about with altered sodium intake, as with changes in GFR to regulate the excretion of sodium.

*Figure 10.5*: The pathway by which a decrease in aldosterone secretion could restore sodium balance, following an increase in sodium intake
10.4 Worked examples

The following is a series of problem scenarios that people who work in the heat commonly ask questions about. Each issue or problem is stated, and the effects and outcomes are discussed. Recommendations are made regarding how to avoid or correct such problems.

1. What happens when a person sweats profusely, and therefore loses salt from the skin, during heat exposure?

When there is a decreased sodium load in the body, due to sweating, the body has several regulatory mechanisms to restore the salt balance. These are summarised in Figure 10.6.

![Figure 10.6: Summary of the body’s responses to low sodium levels](image)

Since an average person in the UK ingests approximately 4 grams of sodium, and only 0.5 grams are required for the obligatory salt losses in the faeces and everyday sweat, the body usually will not be in salt deficit following sweating during heat exposure. This is because the concentration of sodium in sweat is around 0.4 - 1.2 grams/litre, depending upon the acclimatisation state of the individual. Salt supplementation
previously advised for hot climates is therefore only thought necessary when excretory losses of sodium are in excess of normal intake. This would require daily sweat losses of 2-3 litres for an unacclimatised individual with an intake of 4 grams per day of sodium, or over 3 litres per day if acclimatised. Clearly then, it is advantageous, in terms of sodium balance, to be fully acclimatised.

Therefore, the following guidelines regarding salt supplementation are appropriate before and during work in the heat:

Table 10.7: Salt supplementation for work in the heat

<table>
<thead>
<tr>
<th>Daily sweat loss</th>
<th>Acclimatised</th>
<th>Non-acclimatised</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;2 litres</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>2-3 litres</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>&gt;3 litres</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Salt supplementation (✓) necessary or (✗) not necessary

Where salt supplementation is necessary, it may be in the form of extra salting of food or an electrolyte drink. Salt tablets are not advisable. If it is anticipated that sweat rates will require salt supplementation, measures should be taken before and during heat exposure, rather than afterwards.

2. How will diuretics (medication, caffeine, alcohol) affect a person during work in the heat?

Diuretics are agents that act to increase the volume of urine excreted and thus promote fluid loss from the body. Diuretics in the form of medication may be used, for example, to treat people with blood pressure problems. They function by inhibiting tubular reabsorption of sodium, so that more sodium is excreted from the body, and water is also lost by osmosis. There are a number of diuretic drugs that act on the nephron in different ways (for example, inhibiting sodium transport or the action of aldosterone), but all ultimately increase body water loss. Medical advice should be sought if diuretic drugs are prescribed during a time where heat exposure is necessary in the work place.
Alcohol acts as a diuretic in that it inhibits the secretion of ADH, which normally brings about water conservation. This causes the inappropriate loss of water, and is termed water diuresis. Typically, more water is lost in the urine than is consumed in the alcoholic beverage, so in spite of substantial fluid ingestion, dehydration occurs. Therefore, if alcohol has been consumed the night prior to heat exposure, it is likely that a person will begin work in a hypohydrated state, unless rehydration takes place. Water should be consumed prior to sleeping, upon rising, and regularly before during and after heat exposure (see sections 5 and 6 for specific recommendations).

Caffeine also acts as a diuretic. However, the diuretic effect is apparently overstated (Maughan, 1998), and avid caffeine consumers should not be discouraged from drinking such beverages, as fluid is still in good supply from consuming them. This said, water and fluids with controlled amounts of sodium (e.g. squash) should be consumed in addition.

3. Is there a danger of drinking too much to compensate for sweat loss during heat exposure?

Drinking excessive amounts of water without excessive amounts of salt does not result in abnormally high blood pressure (hypertension). This is because although the water enters the blood, causing a temporary rise in blood volume, it also dilutes the blood. A dilution of the blood results in a decreased plasma osmolality, which prevents the secretion of ADH (via stimulation of the baroreceptors and inhibition of the osmoreceptors). Inhibition of ADH secretion means that less filtrate is reabsorbed by the kidneys, and therefore a larger volume of urine is excreted following the water ingestion (see Figure 10.7).
Figure 10.7: Regulatory mechanisms to deal with excess body water
4. What is the best drink for use with work involving heat exposure?

Drinking requirements should be altered according to the length of exposure, which should ideally be anticipated. These requirements are shown in Table 10.8.

<table>
<thead>
<tr>
<th>Length of heat exposure</th>
<th>Drinking requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 60 mins</td>
<td>Plain water – from a safe source and cool</td>
</tr>
<tr>
<td>&gt; 60 mins</td>
<td>Flavoured beverage (no more than 8% carbohydrate, or 2 tbsp sugar per litre of water), cool</td>
</tr>
<tr>
<td>&gt; 240 mins</td>
<td>Above flavoured beverage supplemented with 1 tsp of salt per litre of beverage</td>
</tr>
</tbody>
</table>

10.5 Summary

This model of hydration aims to provide knowledge and practical information at all levels; it can be used as a learning tool or a reference manual, and incorporates text, diagrams and flowcharts to aid in understanding. The range of specific scenarios could be improved by carrying out an investigation of user requirements. This wider range of problem topics may include protective clothing, effects of repeated exposures, and more task specific problems.

The overall chapter aim was to provide an in-depth understanding of the concepts of body water balance in order that a user may then be able to provide appropriate advice in a variety of situations. Now that this is possible, it is important to tackle any practical issues that might prevent such advice being implemented. The next chapter uses fire training instructors as an example of how guidelines may be applied and the difficulties that may occur.
Chapter 11
Chapter 11

PRACTICAL ISSUES THAT MAY PREVENT THE IMPLEMENTATION OF A FLUID INTAKE REGIME FOR FIRE TRAINING INSTRUCTORS

11.1 Introduction
The lack of detailed fluid intake guidelines currently provided for the Fire Service was discussed in Chapter 6. The study of firefighter recruits in Chapter 7 showed that they did not have a significant dehydration or heat strain problem during the training they received. However, this may not be the case operationally, and any recruit may work as a fire training instructor in the future. It was shown in Chapter 8 that the fire training instructors from the three brigades studied were not sufficiently hydrated for the work they were carrying out. When a fluid intake regime for the instructors was implemented under controlled conditions (Chapter 9), levels of hypohydration and core temperature were significantly reduced, and the adoption of such a regime during work in a firehouse may lessen the likelihood of an instructor or recruit incurring heat strain. Chapter 10 provided a method whereby an in-depth understanding of the concepts of body water balance could be gained, and practical advice could then be provided in a situation such as that for the working environment of a fire training instructor. The aim of this chapter is to investigate any practical issues that may hinder the implementation of such advice, and this will complement the physiological detail provided in Chapter 10.

11.2 Method
The approach taken in this study was to provide the subjects with advice regarding remaining well-hydrated during their work, and then to investigate how effective they considered the advice to be and what problems they incurred during its implementation.
11.2.1 Subjects

Subjects gave voluntary and written informed consent, and adhered to the regulations set out in the Loughborough University Human Thermal Environments Laboratory’s ‘Application to Take Part in Thermal Experiments’ and Loughborough University health screen questionnaire (Appendix I).

The subjects that participated in this study were firefighter recruits (n=128) and fire training instructors (n=88) taking part in hot fire training at five different geographical locations (Loughborough Fire Training Unit; Smethwick Firehouse; Oldbury Firehouse; Coventry Firehouse; and the Fire Service College). Figures 11.1 and 11.2 show which brigades the subjects belonged to, and the proportions thereof.

![Figure 11.1: Brigades to whom the firefighter recruits subjects belonged](image)
All subjects were male, except 3 female recruit subjects. Anthropometric measurements of height and weight were taken (according to the equipment and techniques described in Section 2.2.1), and subject age was also noted.

The firefighter recruits had the following personal characteristics: a mean (± SD) age of 23 ± 5 yr, height of 1.85 ± .07 m, and weight of 79.2 ± 5.6 kg. The fire training instructors had the following personal characteristics: a mean (± SD) age of 41 ± 6 yr, height of 1.80 ± .04 m, weight of 83.1 ± 4.6 kg, and 22 ± 6 yr number of years experience.

11.2.2 Experimental design

The experimenter was present to lecture to the subjects on one day, and carry out the experimental work on a subsequent day. All subjects were given the lecture on the day prior to the hot wear. This incorporated the benefits of being well-hydrated during work in the heat, and provided, in the form of a booklet, the fluid intake guidelines that were developed from previous work and used during the study in Chapter 9 (the MIX condition), shown below. The subjects were also informed of the
strong diuretic effect alcohol has on the body, and to bear it in mind the evening before the hot wear. The fluid intake guidelines were provided, but not enforced.

- (Volume 1) 500 ml of squash 2 hours before hot wear 1
- (Volume 2) 300 ml of squash 15-20 minutes before hot wear 1
- (Volume 3) 200 ml of water every 20 minutes during hot wear 1
- (Volume 4) 200 ml of squash every 20 minutes during the rest break
- (Volume 5) 300 ml of squash 15-20 minutes before hot wear 2
- (Volume 6) 200 ml of water every 20 minutes during hot wear 2
- (repeat cycle if necessary for further hot wears)
- (Volume 7) 1000 ml of squash after hot wear 2 (within 30 minutes of exiting the firehouse)

Subjects were provided with recording sheets for all fluid intake from 1800 hrs on the night previous to the hot wear until 1800 hrs on the evening of the hot wear. Subjects were also asked to record how many units of alcohol they consumed the evening prior to the hot wear (they were given information to help calculate this).

On the day of the hot wear, fluids and measuring jugs were provided for subjects in the debrief room at each of the hot fire training locations. A sign providing details of the fluid intake regime was placed by the drinks. No encouragement to drink was provided by the experimenter, but information was provided if sought, as the experimenter was always available throughout the day. The hot wear training then took place as normal. The length of the hot wears and the training day varied as it normally would. This was dependent on factors such as the ratio of instructors to recruits, the size of the firehouse, the time of arrival of the recruits, and whether gas or carbonaceous fire was used.

11.2.3 Environmental conditions

The data was gathered over a total of 34 hot fire training days. Since the aim of the experiment was to determine practical issues of implementing a fluid intake regime during normal working practises, the training took place without interference from the experimenter. Therefore, no constraints were placed on the operating parameters of
the fire houses. Temperatures inside the firehouses were measured every minute using shielded air temperature sensors situated at 1 and 2 meters at different sites throughout the firehouses. The means and ranges are shown in Table 11.1. The data from temperature sensors located in crib rooms with fires was not considered in the mean values, as it is possible that the sensors were influenced by radiant heat (Table 11.1). Temperatures were displayed in the control rooms adjacent to the firehouses throughout the exposures. Humidity probes were only available at the Fire Training Unit in Loughborough. There is a large range in humidity readings, as on some occasions humidity sprays were used during training. Dry bulb temperature and relative humidity were measured outside the firehouses where subjects rested, using a whirling hygrometer (Casella, London, BS 2842/66). Table 11.1 also provides the mean number of hot wears in a training day and the mean duration of the hot fire training sessions.

11.2.4 Questionnaires

The questionnaire was developed with several fire training instructors from the Loughborough Fire Training Unit, who did not take part in the full study. They provided comments on the information and issues they thought relevant, and the questionnaire was developed in order to quantify that information. In the full study subjects were asked to complete a questionnaire regarding their experience in incorporating the fluid intake regime into hot wear training. The questionnaires were anonymous in order that subjects did not feel under pressure to answer in a particular way. Each of the questions is presented in the results section.

Table 11.1: Duration and environmental parameters of the hot fire training sessions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean (± SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temp at 1 metre (°C)</td>
<td>59.6 ± 7.2</td>
<td>51.0 - 65.0</td>
</tr>
<tr>
<td>Air temp at 2 metres (°C)</td>
<td>173.2 ± 10.5</td>
<td>153.0 - 198.0</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>63.1 ± 9.3</td>
<td>50.0 - 78.0</td>
</tr>
<tr>
<td>Dry bulb temp (°C)</td>
<td>17.6 ± 4.8</td>
<td>11.5 - 20.2</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>54.1 ± 2.0</td>
<td>51.9 - 57.3</td>
</tr>
<tr>
<td>Number of hot wears during a training day</td>
<td>2.2 ± 0.5</td>
<td>1 - 3</td>
</tr>
<tr>
<td>Duration of each hot wear (hrs: mins)</td>
<td>00:25 ± 00:13</td>
<td>00:08 - 01:10</td>
</tr>
</tbody>
</table>

* only at the Loughborough Fire Training Unit (n=25)
11.3 Results

The results from the questionnaires are presented with each question.

11.3.1 Question 1

**How many units of alcohol did you consume last night?**

The recruits consumed a mean (±SD) of 0.8 ± 1.3 units of alcohol, with a range of 0 – 6 units, the night prior to the day of training. The instructors consumed a mean (±SD) of 1.0 ± 1.8 units of alcohol, with a range of 0 – 8 units, the night prior to the day of training. 66.4% and 47.7% of the recruits and instructors respectively did not consume any alcohol at all the night prior to the day of training.

11.3.2 Question 2

**How does this compare to the way you would normally drink (alcohol) the night before a hot wear session?**

The distribution of responses is shown in Table 11.2. For both recruits and instructors the amount of alcohol consumed was deemed to be the same as usual for most subjects.

<table>
<thead>
<tr>
<th>Response</th>
<th>Recruits*</th>
<th>Instructors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency</td>
<td>Percentage (%)</td>
</tr>
<tr>
<td>More than usual</td>
<td>18</td>
<td>21.4</td>
</tr>
<tr>
<td>Same as usual</td>
<td>57</td>
<td>67.9</td>
</tr>
<tr>
<td>Less than usual</td>
<td>9</td>
<td>10.7</td>
</tr>
<tr>
<td>Total</td>
<td>84</td>
<td>100</td>
</tr>
</tbody>
</table>

* For 44 of the recruits it was their first hot wear, and therefore, they could not make the comparison (n=84)

11.3.3 Question 3

**Did you manage to drink all the recommended volumes during the day?**

If a subject did not consume a particular recommended fluid volume, they were asked to note it down. The distribution of responses is shown in Table 11.3. A high proportion of both recruits and instructors managed to consume all the recommended fluid volumes.
Table 11.3: Responses regarding consumption of all the recommended volumes during the day

<table>
<thead>
<tr>
<th>Response</th>
<th>Frequency</th>
<th>Percentage (%)</th>
<th>Instructor Frequency</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>87</td>
<td>68</td>
<td>66</td>
<td>75</td>
</tr>
<tr>
<td>No</td>
<td>41</td>
<td>32</td>
<td>22</td>
<td>25</td>
</tr>
</tbody>
</table>

11.3.4 Question 4

If not, which volume (s) did you not drink?

The distribution of responses is shown in Table 11.4. For recruits, the most commonly missed volumes were Volumes 6 and 3 (200 ml water every 20 min during hot wear 2 and 1 respectively). The frequency with which they were missed was considerably higher than other volumes, but Volumes 2 and 5 (300 ml squash 15-20 minutes before hot wear 1 and 2 respectively) were the next most commonly missed.

The spread of volumes missed was greater for instructors. For instructors, the most commonly missed volumes were Volumes 2, 3 and 6, closely followed by Volume 5.

In essence, the recruits and instructors experienced problems consuming fluids at the same times during the day of training, ie. directly before and during the hot wears.

Table 11.4: Volumes of recommended drinks missed throughout the day of training

<table>
<thead>
<tr>
<th>Volume missed</th>
<th>Recruits Frequency</th>
<th>Percentage (%)</th>
<th>Instructors Frequency</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume 1</td>
<td>3</td>
<td>2.3</td>
<td>2</td>
<td>2.3</td>
</tr>
<tr>
<td>Volume 2</td>
<td>13</td>
<td>10.2</td>
<td>10</td>
<td>11.4</td>
</tr>
<tr>
<td>Volume 3</td>
<td>19</td>
<td>14.8</td>
<td>10</td>
<td>11.4</td>
</tr>
<tr>
<td>Volume 4</td>
<td>3</td>
<td>2.3</td>
<td>1</td>
<td>1.1</td>
</tr>
<tr>
<td>Volume 5</td>
<td>11</td>
<td>8.6</td>
<td>9</td>
<td>10.2</td>
</tr>
<tr>
<td>Volume 6</td>
<td>21</td>
<td>16.4</td>
<td>10</td>
<td>11.4</td>
</tr>
<tr>
<td>Volume 4a*</td>
<td>1</td>
<td>0.8</td>
<td>2</td>
<td>2.3</td>
</tr>
<tr>
<td>Volume 5a*</td>
<td>3</td>
<td>2.3</td>
<td>5</td>
<td>5.7</td>
</tr>
<tr>
<td>Volume 6a*</td>
<td>2</td>
<td>1.6</td>
<td>4</td>
<td>4.5</td>
</tr>
<tr>
<td>Volume 7</td>
<td>3</td>
<td>2.3</td>
<td>1</td>
<td>1.1</td>
</tr>
</tbody>
</table>

* These volumes denote fluid intake during a third hot wear (n=3)
11.3.5 Question 5

For each volume missed (if any) please give a reason, using the key provided. The subjects assigned those volumes that were missed during the course of the day with a reason for not consuming the beverage. The breakdown of reasons for recruits is shown in Figure 11.3, and that for instructors is shown in Figure 11.4. Each of the Reasons 1-5 given in the key for those figures is specific; however, Reason 6 was 'Other', and subjects were asked to specify what this was. For both groups, on each occasion when Reason 6 was given, the subject specified that they forgot to drink the particular volume of fluid.

For both recruits and instructors, the reasons for not consuming fluids directly before the hot wears tended mainly to be due to inconvenience and lack of time. However, during the hot wears, the reasons given by both groups for not consuming fluids were more diverse. As well as inconvenience and lack of time, feelings of fullness and the need to urinate too often were felt to be a problem. Interestingly, on the very few occasions (n=3) that Volume 7 (1 litre squash after hot wear 2) was not consumed, the reason was always because the subject forgot.
Figure 11.3: Frequency of missed fluid volumes and reasons given by recruit subjects

Key:

<table>
<thead>
<tr>
<th>Volume</th>
<th>Description</th>
<th>Reason</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vol 1</td>
<td>500 ml squash 2 hours before hot wear</td>
<td>R1</td>
<td>Inconvenience</td>
</tr>
<tr>
<td>Vol 2</td>
<td>300 ml squash 15-20 minutes before hot wear</td>
<td>R2</td>
<td>Lack of time</td>
</tr>
<tr>
<td>Vol 3</td>
<td>200 ml water every 20 minutes during hot wear</td>
<td>R3</td>
<td>Feeling of fullness</td>
</tr>
<tr>
<td>Vol 4</td>
<td>200 ml squash every 20 minutes during rest break</td>
<td>R4</td>
<td>The need to urinate too often</td>
</tr>
<tr>
<td>Vol 5</td>
<td>300 ml squash 15-20 minutes before hot wear</td>
<td>R5</td>
<td>Drinks were not palatable</td>
</tr>
<tr>
<td>Vol 6</td>
<td>200 ml water every 20 minutes during hot wear</td>
<td>R6</td>
<td>Other (please specify)</td>
</tr>
<tr>
<td>Vol 7</td>
<td>1000 ml squash after hot wear</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Vols 4a, 5a & 6a are the same as Vols 4, 5 & 6 (but for a third hot wear)

Figure 11.4: Frequency of missed fluid volumes and reasons given by instructor subjects
11.3.6 Question 6

Which did you rely on most for drinking information?

The sources of information used by both groups are shown in Figure 11.5. The source most used by recruits for drinking information was their booklet (n=68), followed by the sign by the drinks table (n=32). The most frequently used source for the instructors was different, however, as most preferred to rely on each other (n=31), and then on the sign by the drinks table (n=30). The fact that very few subjects relied on the experimenter for information (n=3 for recruits and n=4 for instructors) is favourable, as this would not be possible under normal conditions. In addition, very few of the recruits or instructors (n=7 and n=6 respectively) relied on memory as an information source, which indicates that prompts would be necessary, at least while subjects became familiar with the drinking regime.

![Figure 11.5: Sources of drinking guideline information used](image)

11.3.7 Question 7

How does the total volume compare with what you would normally drink during a day of hot wears?

The majority of the recruits and instructors indicated that by following the drinking regime to the extent that they did, they consumed more fluid than they normally would have on a similar day of training (Table 11.5). Very few subjects from either group reported that the volume consumed was the same as or less than usual.
Table 11.5: Comparison of volume consumption during a normal hot wear and this wear

<table>
<thead>
<tr>
<th>Response</th>
<th>Recruits</th>
<th>Instructors</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency</td>
<td>Percentage (%)</td>
<td>Frequency</td>
<td>Percentage (%)</td>
</tr>
<tr>
<td>More than usual</td>
<td>77</td>
<td>60.2</td>
<td>86</td>
<td>97.7</td>
</tr>
<tr>
<td>Same as usual</td>
<td>6</td>
<td>4.7</td>
<td>2</td>
<td>2.3</td>
</tr>
<tr>
<td>Less than usual</td>
<td>1</td>
<td>0.8</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>N/A*</td>
<td>44</td>
<td>34.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>128</td>
<td>100</td>
<td>88</td>
<td>100</td>
</tr>
</tbody>
</table>

* For 44 of the recruits it was their first hot wear, and therefore, they could not make the comparison (n=84)

11.3.8 Question 8

How do these drink types compare with what you would normally drink?

Subjects indicated which beverage types they would normally drink more or less of on a normal day of training (Table 11.6). An extremely high percentage of subjects reported that they would normally consume more caffeine based drinks (n=62 for recruits and n=83 for instructors). 50% of the recruits would normally have consumed sports drinks (≤8% concentration), whereas the instructors relied on them less (17.0%). A similar proportion of recruits and instructors reported that they would normally consume less water (51.2% and 59.1% respectively), and the majority of both recruits and instructors normally consumed less squash (84.5% and 97.7%).

Table 11.6: Comparison of types of fluid consumed during a normal hot wear and this wear

<table>
<thead>
<tr>
<th>‘I would normally drink…’</th>
<th>Recruits*</th>
<th>Instructors</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>More (%)</td>
<td>Less (%)</td>
<td>More (%)</td>
<td>Less (%)</td>
</tr>
<tr>
<td>Caffeine based drinks</td>
<td>73.8</td>
<td>11.9</td>
<td>94.3</td>
<td>5.7</td>
</tr>
<tr>
<td>Carbonated drinks</td>
<td>39.3</td>
<td>8.3</td>
<td>9.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Sports drinks (≤8% concentration)</td>
<td>50.0</td>
<td>1.2</td>
<td>17.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Sports drinks (&gt;8% concentration)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Milk</td>
<td>1.2</td>
<td>0.0</td>
<td>3.4</td>
<td>2.3</td>
</tr>
<tr>
<td>Water</td>
<td>7.1</td>
<td>51.2</td>
<td>18.2</td>
<td>59.1</td>
</tr>
<tr>
<td>Squash</td>
<td>3.6</td>
<td>84.5</td>
<td>2.3</td>
<td>97.7</td>
</tr>
<tr>
<td>Juice</td>
<td>2.4</td>
<td>0.0</td>
<td>3.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Other</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

* For 44 of the recruits it was their first hot wear, and therefore, they could not make the comparison (n=84)
11.3.9 Questions 9 & 10

Were the drinks in a convenient place? If not, where would they have been better placed?

As shown in Table 11.7, 21.1% of the recruits and 36.4% of the instructors felt that the drinks were not necessarily in a convenient position. Those subjects were then asked where they thought the drinks might have been better placed (Table 11.7). The most common response from both groups of subjects (55.6% for recruits and 59.4% for instructors) was that the drinks would be best placed at several of the locations listed in Table 11.7. The next most common response (22.2%) from the recruits was that the drinks should be placed in the recruit waiting area on the fire ground. However, the instructors' next most common response (21.9%) was that the drinks should be placed in the fire house control room. It is clear that the two groups of subjects have different requirements in this respect.

Table 11.7: Location of liquids for consumption during hot wears

<table>
<thead>
<tr>
<th>Were the drinks in a convenient place?</th>
<th>Recruits</th>
<th>Instructors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes (%)</td>
<td>No (%)</td>
<td>Yes (%)</td>
</tr>
<tr>
<td>78.9</td>
<td>21.1</td>
<td>63.6</td>
</tr>
</tbody>
</table>

If not, where would they have been better placed?

<table>
<thead>
<tr>
<th>Location</th>
<th>Recruits (%)</th>
<th>Instructors (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recruit waiting area (on the fire ground)</td>
<td>22.2</td>
<td>9.4</td>
</tr>
<tr>
<td>In BA maintenance room</td>
<td>3.7</td>
<td>6.3</td>
</tr>
<tr>
<td>In a room adjacent to fire house</td>
<td>7.4</td>
<td>3.1</td>
</tr>
<tr>
<td>Immediately outside the firehouse</td>
<td>11.1</td>
<td>0.0</td>
</tr>
<tr>
<td>In fire house control room</td>
<td>0.0</td>
<td>21.9</td>
</tr>
<tr>
<td>At several or all of the locations listed above</td>
<td>55.6</td>
<td>59.4</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
11.3.10 Questions 11 & 12

Did you use a drinking bottle? If you did use one, did it make it easier for you to drink more often than not using one? If you did not use one, do you think it would have made it easier for you to drink more often?

The majority of recruits (82.0%) used drinking bottles (Table 11.8) (recruits are now issued with them), and 93.0% of the recruits felt that using one would aid them in drinking more often during a training day such as this. Even though the majority of the instructors (55.7%) used drinking bottles, the proportion was somewhat less than the recruits. However, 81.8% of the instructors felt that using one would aid them in consuming more fluid throughout training.

Table 11.8: Use of drinking bottles during the hot wear day

<table>
<thead>
<tr>
<th>Did you use a drinking bottle?</th>
<th>Recruits</th>
<th>Instructors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes (%)</td>
<td>No (%)</td>
<td>Yes (%)</td>
</tr>
<tr>
<td>82.0</td>
<td>18.0</td>
<td>55.7</td>
</tr>
</tbody>
</table>

If you did use one, did it make it easier for you to drink more often than not using one? If you did not use one, do you think it would have made it easier for you to drink more often?

Table 11.9: Responses as to whether the drinking regime made subjects feel better than usual

<table>
<thead>
<tr>
<th>Did you feel better for following the drinking regime?</th>
<th>Recruits</th>
<th>Instructors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes (%)</td>
<td>No (%)</td>
<td>Yes (%)</td>
</tr>
<tr>
<td>93.0</td>
<td>7.0</td>
<td>81.8</td>
</tr>
</tbody>
</table>

11.3.11 Question 13

Did you feel better for following the drinking regime?

The majority of recruits and instructors reported that they felt better than usual for following the drinking regime before, during and after the wear (Table 11.9).

Table 11.9: Responses as to whether the drinking regime made subjects feel better than usual

<table>
<thead>
<tr>
<th>Did you feel better for following the drinking regime?</th>
<th>Recruits</th>
<th>Instructors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes (%)</td>
<td>No (%)</td>
<td>Yes (%)</td>
</tr>
<tr>
<td>77.3</td>
<td>22.7</td>
<td>71.6</td>
</tr>
<tr>
<td>92.2</td>
<td>7.8</td>
<td>81.8</td>
</tr>
<tr>
<td>99.2</td>
<td>0.8</td>
<td>93.2</td>
</tr>
</tbody>
</table>

* For 44 of the recruits it was their first hot wear, and therefore, they could not make the comparison (n=84)
11.3.12 Question 14

Would you continue to drink in this manner without supervision during hot wears?

For the recruits, of the 3.9% (n=5) that responded ‘no’, 4 subjects said that they would continue to follow a form of the guidelines, but with smaller volumes of fluid, and 1 subject did not respond at all. 26.1% of the instructors (n=23) said that they would not continue to follow the guidelines. Of these, 16 said they would consume more fluid and avoid caffeine, but not intake particular volumes as it was too time consuming to calculate. Three of the instructors said that they would not be able to consume fluid during the training sessions, only before and after, 3 subjects did not respond, and 1 subject said he would continue to drink only coffee all of the time.

Table 11.10: Responses as to whether subjects would continue to follow the fluid intake guidelines

<table>
<thead>
<tr>
<th>Recruits</th>
<th>Instructors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes (%)</td>
<td>No (%)</td>
</tr>
<tr>
<td>96.1</td>
<td>3.9</td>
</tr>
</tbody>
</table>

11.4 Discussion

The aim of this chapter is to identify practical issues that may affect the implementation of a fluid intake regime during training sessions at firehouses. Although this work was carried out at five locations, and the subjects represented 17 different brigades, it is not envisaged that the facilities provided at other fire stations will differ significantly from those available in this study.

Due to the strong diuretic effect of alcohol, it would be advisable to avoid consuming alcohol the evening prior to a day of hot wear training, which 66.4% and 47.7% of the recruits and instructors respectively did. Current guidelines (Health Education Authority, 1999) suggest that daily intake for males should not be above 3-4 units, and for females 2-3 units. The mean intake for both groups on the evening prior to the hot wear training was lower then these limits (0.8 ± 1.3 units for recruits and 1.0 ± 1.8 units for instructors), but when considering the range (0-6 units for recruits and 0-8 units for instructors, some individuals exceeded these limits. Further education regarding the effects of alcohol on hydration state and performance may be required.
A high percentage of recruits and instructors (68% and 75% respectively) managed to consume all the recommended volumes of fluids throughout the day of training, which indicates that the implementation of such a fluid intake regime is possible. However, the issues that affected those not able to completely follow the regime are of interest. The recruits and instructors experienced problems in consuming fluids at the same times during the day of training. These were directly before and during the hot wear. The main reasons given for missing volumes before the hot wear were inconvenience and lack of time. The time directly before a hot wear is usually spent servicing SCBA sets by both instructors and recruits. In addition, the instructors also prepare the firehouse for use. A solution to this problem therefore may be to prepare slightly earlier, and attempt to incorporate sipping from a drinking bottle into these tasks. The provision of fluids at several locations around the fire training area (as discussed later) may also aid this process. In addition, although the subjects were provided with measuring jugs, a more convenient method may be to provide cups and drinking bottles with volume gradations on them. Inconvenience and lack of time were also given as main reasons for not consuming fluids during the hot wear. Wearing SCBA does make drinking difficult; however, all subjects had rest breaks at some stage during each hot wear session, so drinking was possible. It should be emphasised, though, that those subjects who did not manage to consume all the recommended volumes of fluid were in the minority.

The information booklet that subjects were provided with proved to be a valuable resource for the recruit subjects, as did the sign by the drinks table, which provided the fluid intake guidelines. The instructors preferred to rely on a combination of each other and the sign by the drinks table. It may have been difficult to refer to their booklets whilst they were in and around the firehouse, whereas the recruits had a waiting area. Since few of the subjects (n=7 for recruits and n=6 for instructors) relied on memory, it seems that prompts, in the form of booklets and signs at various locations, would be necessary as part of a fluid intake regime.

The majority of the subjects (78.9% for recruits and 63.6% for instructors) felt that the drinks were in a convenient location (in the debrief room). Of those subjects who did not, most subjects indicated that the drinks would be best placed at several locations
around the fire training area, such as the recruit waiting area, the SCBA maintenance room, and in the firehouse control room.

The use of drinking bottles was frequent within both subjects groups, particularly the recruits, who are now issued with them (82% for recruits and 55.7% for instructors). The majority of subjects in both groups felt that the use of drinking bottles would aid them in following the drinking regime. As mentioned previously, clear (those currently issued are opaque) drinking bottles with volume gradations marked on them may be more convenient to use. An important point to note is the regular sterilisation of drinking bottles, even if they are only used by the same person.

An extremely high percentage of subjects reported that they would normally drink more caffeine based beverages (73.8% for recruits and 94.3% for instructors), which is in keeping with the 'strong tea drinking tradition' discussed in earlier chapters. This indicates that education may be required as to the benefits of avoiding caffeine during training days such as these, should this fluid intake regime be implemented.

Compared to a normal day of training such as this, the majority of the recruits and instructors felt better before, during and after the training. In addition, a very high percentage of both groups of subjects indicated that they would continue to follow such a fluid intake regime unsupervised in the future. Since the questionnaires were anonymous, it is felt that these responses were honest opinions. Subjective judgements such as these are important if the implementation of a fluid intake regime is to be a success.

11.5 Conclusions

It is possible to implement an effective fluid intake regime during hot fire training at a firehouse. The main aim of the study was to identify problems in implementing such a regime. Consideration should be given to the placement of both fluids and intake guidelines. Each should be placed in several locations around the training area. Since problems of inconvenience and lack of time are experienced throughout such days of training, fluids should be made as readily available as possible. The use of clear, marked drinking bottles would be effective in encouraging regular fluid consumption.
The implementation of such a fluid intake regime would be of greater benefit when used in tandem with education regarding work in the heat, and how this can be affected by factors such as regular fluid intake and the consumption of diuretics. The following chapter addresses the need to provide fire training instructors with correct information on heat strain and dehydration in order that they have an understanding of the processes when working themselves, and when providing recruits with advice. This then complements the advice being provided.
Chapter 12
Chapter 12

GUIDANCE DOCUMENT ON CONTROLLING HYDRATION STATE FOR WORK IN THE HEAT

12.1 Introduction
The aim of this chapter is to assimilate existing knowledge of hydration issues, the specific needs of a user population (i.e. the Fire Service), and relevant and practical guidance.

Many studies have been carried out to identify factors that can stimulate or enhance drinking during or after exposure to stressful environments. These include acclimation (Greenleaf et al, 1983; Strydom et al, 1966), optimal drink temperature (Adoph, 1947; Boulze et al, 1983; Szlyk et al, 1990), additional flavourings (Hubbard et al, 1984; Spioch & Nowara, 1980; Szlyk, 1989b) addition of electrolytes including citrus drinks (Nose et al, 1988b, 1988c; Spioch & Nowara, 1980), increased hypovolemia (Steggerda, 1941), increased plasma renin-angiotensin II concentration (Fitzsimons, 1966, 1969) and eating food (Adoph, 1947; Maughan et al, 1996; Szlyk et al, 1990). The majority of these studies were carried out in controlled laboratory conditions. However, people whose jobs involve heat exposure do not work in such environments. Therefore, it is necessary to combine the results of such carefully controlled studies with field studies and practical guidance that will allow the implementation of beneficial hydration practises.

The following document is intended for use by fire training instructors, but it could also be used by general firefighters, both operationally and during training. In light of the current general advice available to brigades (DCOL, 1997), it aims to provide background information and detailed guidance on remaining well-hydrated during work in the heat. It takes into account the experimental work carried out in previous chapters, the specific needs of firefighters during their work in the heat, and available literature. However, it may be adapted for other jobs that require work in the heat. Since the problems of dehydration are often encountered with heat strain, especially during firefighting, the relevant information has been provided. The level of detail
given is aimed at fire training instructors, but a one-page summary has been provided at the end, either for their quick reference, or for a general firefighter who may require less detail, but concise guidance. In addition, a glossary has been provided to explain some of the more scientific terms.

12.2 Guidance document

GUIDANCE DOCUMENT:
HEAT STRAIN & DEHYDRATION ADVICE FOR FIREFIGHTING

12.2.1 Heat strain and dehydration – how do they occur?
Heat strain is a potential problem for any person exposed to heat for any length of time. There are three main factors that may lead to a rise in body temperature that could cause heat strain: the environment, the clothing worn and the work done. The environmental conditions will have a major effect on the level of heat stress incurred. Under normal conditions, the body’s thermoregulatory system is able to cope with the increase in temperature, and will use a number of mechanisms to increase the amount of heat being lost, and therefore maintain the internal core temperature. Once dehydration begins, the body’s capacity to regulate temperature is reduced.

Thermoregulation
As physical work is undertaken, energy is used in order to produce the muscle contractions needed to move the body, and the metabolic rate of the body can increase by 5 to 15 times that of the resting level. The body is inefficient at using energy, and heat is produced as a by-product of this muscular work. As the body heats up, vasodilation will occur in an attempt to regulate temperature. This is the process by which blood flow to the skin is increased, as this allows heat from the blood to be lost due to the cooling effect of the surrounding environment (the blood is also required to serve active muscles and organs). However, when the environmental temperature exceeds the skin temperature, the body is gaining heat by convection, radiation and conduction, so evaporation of sweat is the only avenue for heat loss. Evaporation of sweat from the skin causes an immediate cooling effect. As the body heats up, the
sweat rate will increase in an effort to lose more heat. A high sweat rate is an efficient way to lose heat from the body, but unless this fluid is replaced, dehydration will occur, and may lead to heat strain.

Dehydration
Water is the largest component of the human body, representing between 60-70% of total body weight. A reduction in the amount of body water can have serious or even fatal consequences, because virtually all physiological systems will be affected. Water is used within the body as a medium for biochemical reactions and for carrying body solutes. It is the main component of plasma, which is essential in the maintenance of blood volume. Plasma is also the initial source of fluid for sweat production. In humans, sweating can exceed 1.8 litres per hour. Unless this water is replaced through drinking, the volume of blood in the body will be reduced due to the loss of plasma. Thirst alone should not be relied on as an indicator of the need to drink, since the body will have lost 1-2% of its water and experienced performance decrements before a person feels thirsty. If blood volume is reduced, then more pressure is put on the heart to keep an adequate blood supply to all the areas of the body needing blood, and there will be an increase in heart rate. However, continuous heat-exercise will continue to deplete the body’s water stores. This process of dehydration reduces the volume of the body fluids and makes them more concentrated. In this state, sweat rate and skin blood flow are reduced, thus limiting evaporative heat loss, which accounts for more than 80% of heat loss in a hot, dry environment. For this reason, the body is less able to dissipate heat and core temperature rises.

Heat injury
When dehydration takes place to the extent that the body can no longer regulate temperature, an individual will start to experience heat injury. Heat injury is progressive, and unless the individual is removed from the source of heat stress, they will experience more severe symptoms. The symptoms, cause, treatment and prevention of the stages of heat injury are shown in Table 12.1. Although heat strain is usually associated with work in the heat, it can also occur in relatively cool conditions, for example when a person is working in impermeable protective clothing, such as a gas tight suit.
<table>
<thead>
<tr>
<th>Heat injury type</th>
<th>Symptoms</th>
<th>Cause</th>
<th>Treatment</th>
<th>Prevention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat cramps</td>
<td>Painful muscle spasms in arms, legs &amp; stomach</td>
<td>Exercise in the heat, excessive loss of salty sweat, inadequate salt intake, inadequate acclimatisation</td>
<td>Drink fluids containing salt, rest in a cool environment, add salt to food</td>
<td>Acclimatising to exercise in the heat, consume balanced diet, drinks fluids containing salt</td>
</tr>
<tr>
<td>Heat syncope</td>
<td>Light-headedness or fainting when standing, extreme paleness, fatigue</td>
<td>Reduced blood flow to the head due to increased blood flow to the skin to maximise heat loss</td>
<td>Remove to cooler area, lie down, rest and drink cool fluids</td>
<td>Acclimatising to exercise in the heat, avoid dehydration &amp; prolonged standing. Work intermittently</td>
</tr>
<tr>
<td>Heat exhaustion</td>
<td>Reduced sweating, increased body temperature, strong thirst, lethargic &amp; irritable, low volume of concentrated urine, headache, nausea, clammy &amp; pale skin</td>
<td>Heavy, prolonged sweating, diarrhoea, inadequate fluid intake, unacclimatised to work in the heat, water deficient</td>
<td>Remove to cooler area, lie down, rest and drink cool fluids. Rest until urine colour and volume return to normal</td>
<td>Acclimatising using intermittent work schedule over 5-7 days, supplement salt intake during this time, drink ample fluids, reduce exercise intensity &amp; rest more frequently</td>
</tr>
<tr>
<td>Heat stroke</td>
<td>Excessive body temperature (&gt;40°C), vomiting, little sweating, dry skin, involuntary limb movement, confusion, convulsions, loss of consciousness, coma</td>
<td>Lack of fitness, obesity, excessive alcohol intake in the heat, inadequate acclimatisation, illness, dehydration, failure of the body’s temperature control mechanism</td>
<td>Immediate and rapid cooling by immersion in chilled water, wrap in wet sheets, vigorous fanning with cool air, avoid over cooling. Fatal if untreated</td>
<td>Medical screening of workers, selection of the healthy, fit, young, adequately acclimatised, with constant monitoring of personnel whilst working in the heat. Ensure ample fluids are consumed, avoid dehydration &amp; reduce exercise intensity</td>
</tr>
</tbody>
</table>
Individual characteristics

For a given heat stress situation, individuals will respond differently. The most important factors in influencing individual response to heat stress are fitness and acclimatisation, followed by morphology (body size and composition). However, the relative importance of these factors will be determined by the work situation (eg, neutral, hot-dry, hot-humid, same workload for everybody, percentage of an individual’s maximum workload).

- **fitness** – the fitter a person is, the greater their capacity for an additional increase in cardiac output (heart rate x stroke volume) when necessary
- **acclimatisation** – with increased acclimatisation, an individual will experience a lower core temperature and heart rate for the same work in the heat
- **morphology** – in humans, a bigger subject with a high surface area and mass will generally be at an advantage due to greater heat storage capacity (although may have a higher metabolic rate). People with equal mass, but higher fat content will heat up faster.
- **gender** – once females and males are matched for aerobic fitness, percentage of body fat and size, there is little difference in heat stress response, and some of those differences are climate specific (eg. females often perform better in warm-humid and worse in hot-dry climates)
- **age** – generally, older people have more body fat and are less fit; however, when these differences are corrected for, heat stress response with age disappears (it is very difficult to match older and younger people for body fat and fitness, though)

The body’s water requirements

Even when a person is sedentary in a moderate environment, their body needs 2.5 litres of water per day to replace the water that is lost. Since work in a hot environment can generate sweat rates of up to 1.8 litres/hour, it is clear that water intake needs to be increased significantly in such a situation. *Table 12.2* shows typical human water balance in a moderate environment.
Table 12.2: Daily water balance for an average 75kg man

<table>
<thead>
<tr>
<th>Source</th>
<th>Volume (ml)</th>
<th>Source</th>
<th>Volume (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid food</td>
<td>1000</td>
<td>Lungs &amp; non-sweating skin</td>
<td>700</td>
</tr>
<tr>
<td>Metabolism</td>
<td>350</td>
<td>Sweat</td>
<td>250</td>
</tr>
<tr>
<td>Fluids</td>
<td>1200</td>
<td>Faeces</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Urine</td>
<td>1500</td>
</tr>
<tr>
<td>Total</td>
<td>2550</td>
<td>Total</td>
<td>2550</td>
</tr>
</tbody>
</table>

**Water inputs**

The hydration state of the body refers to how much water is actually present in the body. Water can be added to the body fluids via three sources: the water content of food; the water generated when food is digested; and the water consumed as liquid. The amount of water in food can vary widely: meat is 75% water because it is animal muscle (muscles consist of about 75% water) and fruit and vegetables consist of 60-90% water, whereas many processed, packaged foods contain little or no water. The amount of water in food may become important if an individual is exposed to heat and loses vital body water through sweating. The second source of water input is metabolically produced water. Chemical reactions in the cells convert food and oxygen into energy, producing carbon dioxide and water in the process. Water input is almost solely regulated by the third source, water consumed as liquid. The changes in volume consumed average 1-2 litres per day, but range from less than 1 litre per day to more than 20 litres per day.

**Water outputs**

Water is constantly lost through various mechanisms. When breathing out, the expired air usually has a high content of water (as demonstrated by breathing onto a cold window – a cloud of condensation is clearly seen.) Water is also constantly lost through the skin, either through insensible loss (non-sweating skin) or through sweating. Insensible loss is a continuous process, caused by the pressure gradients between the skin and the environment. If the body has a higher percentage of water than the surrounding air, then water will be lost, through the skin to the environment. Sweating is an ‘active’ process, controlled by the body’s thermoregulatory system as a mechanism for heat loss. Urine production is also a constant process. A person will still produce obligatory urine during dehydration as a means of removing waste.
products from the body. The production of this obligatory urine is necessary, as failure to remove this waste will lead to eventual kidney failure and death. However, in times of dehydration, the kidneys will attempt to conserve body water, and urine will become much more concentrated in waste products. It is this concentration of dissolved waste that gives urine its colour, and allows the use of urine as a measure of hydration state. Therefore, reduced volume and darker coloured urine is a good indicator of dehydration.

12.2.2 How does this translate to the work of a firefighter?
A firefighter's working environment can be hostile. Therefore, in order to prepare for such situations, training must incorporate experience in hostile environments. For this purpose, many brigades now use compartment fire training facilities (or firehouses), which provide realistic training in a hazardous environment. This means that a firefighter should be aware of the consequences of heat exposure both operationally and during training. In both situations firefighters experience hot, humid and often polluted atmospheres, and as a result may incur great levels of physiological strain.

12.2.3 Contributing factors to physiological strain during firefighting
The following factors may work in combination to create a high level of physiological strain for a firefighter at work:

High ambient temperatures
Typical ambient temperatures during firefighting range from 38°C to 66°C, but can be as high as several hundred degrees. Firefighters are taught to stay as low as possible during structural firefighting by crouching or crawling. This is because the temperature gradient is extremely steep, so for example, at a height of 1 metre the air temperature may be 58°C, but at 2 metres it may well be 150°C. Therefore, applying common sense can reduce the heat load experienced.

Workload
Firefighting tasks have been classified as 'hard work', often with an oxygen uptake of 3 litres / minute. Oxygen uptake during stair climbing in protective clothing and breathing apparatus can reach 80% VO2 max, and it has been reported that firefighting
produces an almost maximal heart rate response for prolonged periods. This should be borne in mind when considering fitness regimes; although strength is important, high levels of aerobic fitness are of great benefit when carrying out firefighting tasks, and may lessen the effects of dehydration.

**Weight and insulating properties of PPE**

The weight and insulating properties of firefighting equipment impose additional strain on firefighters. For example, the energy cost of moderate work while wearing firefighting clothing and protective equipment is 33% more than that required to perform the same work without protective clothing and equipment.

Advances in PPE technology now mean that a firefighter is better protected from the external environment than ever before. However, the higher insulation levels provided by fire tunics and trousers, and the 100% coverage of the body surface area, as shown in *Plate 12.1*, mean that there are fewer avenues for heat loss from the body.

*Plate 12.1*: High insulation levels and full body coverage provided by firefighting PPE

**SCBA**

Firefighters must use self contained breathing apparatus (SCBA) when they operate in highly contaminated atmospheres. However, the use of SCBA can cause a significant increase in physiological strain during submaximal work, reducing the working time to exhaustion by 20%, and decreasing the maximal work pace by 20%.
Time pressure
The nature of operational firefighting and rescue is such that great haste is required in order to minimise injury, loss of life and damage to property. In addition to a higher physical workload, this also may lead to lack of preparation with regard to hydration and donning protective clothing correctly to afford maximum protection. Also, since each fire scene often presents unique problems, it is difficult to predict required exposure times.

Clothing micro-environment
The heat balance achieved between a person and their environment is dependent on several factors, including their personal characteristics, their clothing, the task being performed and the thermal environment to which they are exposed. These factors, together with the body’s responses and the thermal properties of the clothing, determine the ‘clothing micro-environment’; that is, the area between the skin and the clothing. The clothing micro-environment is demonstrated in Figure 12.1. For example, if a person carries out a high level of activity whilst wearing heavy clothing, it is likely that there will be a build up of sweat within the clothing. This will increase the relative humidity of the air trapped between clothing layers, and most importantly increase the relative humidity next to the wearer’s skin. High humidity in this air layer may lead to inefficient evaporation of sweat from the skin’s surface, thereby reducing the body’s ability to cool itself effectively. The air layer in the clothing micro-environment can be replaced through pumping at the cuffs and vents, but the design of firekit mean there are few opportunities for this to take place.

Figure 12.1: The clothing micro-environment
Humidity
A hot environment may also be very humid if sprinklers have been activated or if hoses have been applied to a fire. In this situation, the vapour permeable membrane in firekit will not offer good protection to the wearer, as the external environment is able to penetrate the membrane and affect the clothing micro-environment considerably. When the air surrounding the wearer is highly saturated, it becomes increasingly difficult for the wearer to evaporate sweat from the skin. A firefighter would find this environment very difficult to operate in for any length of time.

Dehydration
Often a firefighter cannot avoid some or all of the physiological strains discussed above, such as the hostile environment, the activity level and the use of SCBA and PPE. Although a certain amount of dehydration is inevitable during firefighting activities, advance preparation can make a vital difference to health and performance. Proper hydration is essential to reduce the likelihood of an individual suffering heat strain or experiencing impairment in exercise performance during such tasks.

12.2.4 The effects of heat strain and dehydration during firefighting tasks
Physiological effects
There are many adverse effects of dehydration on humans including the beginning of impaired exercise thermoregulation at about 1% of body weight (water) loss, leading to likely collapse at about 7% of body weight, when exercise and heat are combined (Table 12.3). People who begin exercise with a previously incurred fluid deficit display an impaired ability to dissipate heat during subsequent exercise. They experience a faster rise in core temperature and heart rate; this effect is exaggerated when activity is performed in a hot environment. Core temperature will rise by 0.1-0.4°C for each percent decrease in body weight (depending on exercise intensity and environmental conditions). In moderate environmental conditions, the loss of a relatively large amount of body water (6-7%) has a minimal effect on maximal aerobic power, but may reduce physical work capacity by 20%, i.e. following dehydration, a person could still work at the same rate to supply oxygen to the muscles, but work time would be markedly reduced. Well trained individuals will
show smaller decreases in work time than less trained individuals in this situation. Dehydration does not seem to affect maximal strength or brief sprint running. Reaction time is increased with dehydration, as is the effort required to perform simple tasks. In combination with a hot environment, dehydration is most apparent in tasks requiring stamina; with a body weight loss of 4%, there may be a decrease of almost 50% in physical work capacity and a loss of almost 30% of aerobic power.

Table 12.3: Adverse effects of dehydration on humans by body weight loss

<table>
<thead>
<tr>
<th>% BW loss</th>
<th>Litres for an 75 kg man</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.75</td>
<td>Thirst threshold at rest, decreased thermoregulation during exercise, leading to reduced physical work capacity</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>Stronger thirst, vague discomfort, loss of appetite, sense of oppression</td>
</tr>
<tr>
<td>3</td>
<td>2.25</td>
<td>Increasing haemoconcentration, dry mouth, reduction in urine output</td>
</tr>
<tr>
<td>4</td>
<td>3.0</td>
<td>Increased effort in exercise, flushed skin, impatience, apathy, physical work capacity reduced by 20-30% (reduced by up to 50% in the heat)</td>
</tr>
<tr>
<td>5</td>
<td>3.75</td>
<td>Difficulty in concentrating, headache, impatience, sleepiness</td>
</tr>
<tr>
<td>6</td>
<td>4.5</td>
<td>Severe impairment in exercise temperature regulation, increased HR, risk of heat stroke, increased rate of breathing leading to tingling and numbness of the extremities</td>
</tr>
<tr>
<td>7</td>
<td>5.25</td>
<td>Likely collapse if combined with heat and exercise</td>
</tr>
<tr>
<td>8</td>
<td>6.0</td>
<td>Dizziness, laboured breathing in exercise, mental confusion</td>
</tr>
<tr>
<td>10</td>
<td>7.5</td>
<td>Spastic muscles, inability to balance with eyes closed, general incapacity, delirium, swollen tongue</td>
</tr>
<tr>
<td>11</td>
<td>8.25</td>
<td>Circulatory insufficiency, marked haemoconcentration, marked decreased blood volume, failing renal function</td>
</tr>
<tr>
<td>15-20</td>
<td>11.25 – 15.0</td>
<td>Death</td>
</tr>
</tbody>
</table>

**Cognitive effects**

For many complex industrial tasks, both mental decision making and physiological function are closely related (*Table 12.3*). The heat stress threshold at which cognitive performance is adversely affected depends upon a complex interplay of factors such as the degree of thermal stress, duration of exposure, acclimatisation and the level of tolerance of individuals.

Although the effects of dehydration upon mental performance are poorly reported, the influence of heat stress is well reported and may be similar. High levels of heat stress
are known to have the following effects upon certain tasks, the high performance of which are vital for firefighters:

- decrements in the performance of vigilance tasks (eg. observing colleagues’ actions) mental arithmetic (eg. cylinder and exposure times), and spatial reasoning
- a reduction in reaction time and increase time to make decisions (eg. judgements regarding safety)
- increased number of errors and inaccuracies apparent within a task (eg. operating dangerous machinery)
- an impaired ability to track signals, both auditory and visual (eg. distress signals)

**Physical and mental indicators of dehydration**

Although the prevention of dehydration is the ideal, Table 12.4 is a summary and quick reference guide to the physical and mental indicators of dehydration. If a firefighter begins to notice these symptoms, it is likely that their ability to perform tasks has already diminished, and they may be at risk of suffering heat injury if the situation is not rectified. A firefighter may not always be aware of the presence of such symptoms in themselves, so it is important that colleagues monitor each other.

*Table 12.4: Physical and mental indicators of dehydration*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Indicator of dehydration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweat</td>
<td>High sweat rates (when the equivalent is not replaced). If sweating ceases under continued heat stress, heat illness is underway (see Table 12.1)</td>
</tr>
<tr>
<td>Body temperature &amp; heart rate</td>
<td>Faster rise in core temperature and greater cardiovascular strain compared to carrying out the same tasks when normally hydrated</td>
</tr>
<tr>
<td>Urine</td>
<td>Urine volume and frequency will be reduced and the colour will be darker as dehydration goes on (see Appendix II)</td>
</tr>
<tr>
<td>Skin</td>
<td>When pinched, skin takes longer to return to normal – it is less elastic</td>
</tr>
<tr>
<td>Stamina</td>
<td>Can be greatly reduced - most evident when dehydration is combined with heat</td>
</tr>
<tr>
<td>Appetite</td>
<td>Loss of appetite becomes apparent with dehydration. This can be problematic, both due to the water contained in food, and also that people tend to restore most sweat loss during and after eating. However, food should not be forced on a heat casualty, since this has been shown to increase mortality rate</td>
</tr>
<tr>
<td>Impatience &amp; apathy</td>
<td>Impatience and apathy increase and there may be mood changes– (these may, of course, be a person’s natural characteristics!)</td>
</tr>
<tr>
<td>Concentration</td>
<td>Difficulty in concentrating, confusion, lack of alertness, increase in errors</td>
</tr>
</tbody>
</table>
12.2.5 Operational and training risks for firefighters

Due to nature of the job of a firefighter, the following factors may put them at greater risk of suffering dehydration and heat injury. With careful planning and awareness, they can be avoided.

The effects of dehydration being present at the beginning of the day

This may be the case for several reasons, and will put a firefighter at an immediate physical disadvantage:

- *previous exposures* – either during training or operationally, the physiological effects of previous firefighting work will add up unless proper rehydration has taken place
- *exercise* – sweat rates can often exceed 1 litre per hour during heavy exercise, and such activities, either on or off duty, should include correct hydration procedures
- *habit* – people tend to drink according to social habit (eg. tea break) rather than the body's need for extra fluid, and on many such occasions those drinks contain caffeine, which acts as a diuretic by encouraging the body to lose water (see later)
- *alcohol* – this is a very strong diuretic (causes the body to lose water), and the dehydration effects of consuming large quantities of alcohol the night prior to firefighting work will be very apparent once work in heat commences

Risks to colleagues and students

The effects of dehydration and heat strain on physical performance and mental awareness have been discussed. Should these be apparent during the work of a firefighter, their capacity to carry out rescues, make decisions, and be vigilant of colleagues and students (during training) will be diminished.

Lack of experience

Lack of experience may confound the problem during firefighting. For example, knowledge of how to avoid areas of heat build up during structural firefighting will allow a firefighter to incur a lower heat load.
Repeated call-outs
During operational work, a fire appliance and its crew may be called out repeatedly with little or no time to return to the station. This situation makes advance and continuous hydration more difficult to control. It is not impossible, however.

Nature of call outs
Depending on the geographical location of a fire station, there may be an increase in the number of fire calls during summer that require sustained, heavy work, such as grass and scrubland firefighting. The environment, activity and protective clothing involved in such sustained firefighting increase the likelihood of heat casualties.

Macho attitudes
Firefighters must learn to admit when they are beginning to feel unwell. The consequences of carrying on firefighting tasks whilst suffering severe dehydration and/or heat injury are potentially very dangerous for the individual and their colleagues.

12.2.6 Prevention and reduction of heat strain and dehydration
Incorporating the following procedures into operational and training firefighting work will prevent or reduce the severity of heat strain and dehydration. The measures are straightforward and need not interfere with firefighting activities where adequate manning is provided.

Controlled SCBA work
Where an incident requires SCBA to be worn in a hot environment, the maximum exposure time should be two full cylinders, but with at least 30-40 minutes rest in between them. It should be emphasised that this is a maximum, and certain individuals may tolerate far less exposure time. Caution should be exercised with further SCBA wears at other incidents in the same day, as the effects of heat strain and dehydration may still be apparent.

Clothes underneath firekit
When clothing worn underneath firekit becomes soaked with sweat, and work is to continue, it should be replaced where possible with dry clothing. Sweat is less likely
to evaporate through damp than dry clothing, as the air around the skin will be more saturated, decreasing the body's ability to dissipate heat. Comfort will also be increased with the replacement of dry clothing.

**Work / rest schedules**

An effective way to extend the length of time a firefighter can carry out tasks is to use work / rest schedules. The rest periods allow time to cool down and rehydrate, maintaining high performance levels for longer and delaying the onset of heat related illness. For extended incidents, using a shift pattern to allow rest periods while others work is necessary and feasible.

**Active cooling measures**

Active cooling measures can be used intermittently during firefighting work, and may allow a firefighter to work to a greater capacity and for longer, as rise in core temperature will be reduced. Some examples are:

- *hand cooling in water* – the large surface area to mass ratio of the hand allows effective cooling at the skin's surface, and also blood vessels pass very close to the surface of the skin at the wrist, which allows blood to be cooled before being transported back to the heart and pumped around the body
- *fan cooling* – using fans to cool the torso and head (with the fire tunic open) increases evaporative cooling at the skin, and gives an immediate sense of relief

**Acclimatisation**

Acclimatisation means that for a given work / heat exposure, a person will experience less physiological strain (lower core temperature and heart rate) than when unacclimatised. It is possible for a person to become acclimatised to the heat by repeated exposure and heat-exercise. However, it can take several hours per day for between 4-8 days to achieve, so may be more relevant during training. This acclimatisation to heat allows longer exposure and better work rates due to:

- improvement in evaporative cooling efficiency – sweat will be produced sooner and at greater rates
- improvement of temperature regulation, enabling better performance in the heat
• improved circulatory stability – the heart will cope better with the demands of physical work in the heat

The main problem with acclimatisation is that the increased sweat rate, which although leading to better cooling, will also lead to more rapid dehydration, unless fluid levels are replaced at a greater rate. Firefighters should also be aware that acclimatisation diminishes with lack of heat exposure, and the benefits may be absent upon returning to work after time off. A firefighter should be aware of this and demand less himself/herself when returning to work.

Fitness
Increasing aerobic fitness is of great benefit for work in the heat. Regular aerobic training can often result in an acclimatisation effect, as exercise increases core temperature and sweat rate. This improves the individual response to heat stress, so that heat strain is greatly reduced. In addition, during dehydration, a fitter individual will be able to work for a longer period of time. Improving strength is important for many firefighting tasks, but is of less benefit than improving aerobic fitness for working in the heat. Activities that develop aerobic fitness include jogging, swimming, cycling, rowing, and the emphasis should be on duration rather than intensity.

Temperature monitoring and weighing
Where possible during training, firefighters should attempt to monitor body temperature and body weight loss through sweating. Using a mercury in glass thermometer gives a good idea of body temperature, but it must be placed under the tongue for at least 6 -7 minutes with the mouth closed for the whole time. This should be done both before and after the work period in question, as an individual may have an elevated temperature to begin with, eg. fever. Such temperature monitoring provides an individual with information as to how long and at what work rates it may take them to reach a certain temperature, and how they feel at that temperature. Temperature monitoring may also be used operationally where heat injury is suspected. However, oral temperature is not suitable to be used when breathing apparatus has been worn immediately beforehand.
Monitoring sweat loss is possible using scales to weigh a person before and after a work period (in as few clothes as possible so that sweat trapped in clothing is not counted as still being in the body). This gives an individual an idea of how much sweat they have produced, and therefore how much needs to be replaced. If this technique is to be used, the change in body weight must be corrected for other losses, such as urine and faeces, and gains such as food and drink, which probably means it is more suitable for a training environment. (See section on fluid volume intake).

Urine monitoring

During dehydration, the body will attempt to conserve water by reducing urine output. However, the body produces an obligatory amount of urine, regardless of the state of hydration, as a means of ridding the body of waste products (which is why more water than that lost as sweat should be replaced). It is these waste products that give urine its colour. The reduction in the amount of water added to the urine during dehydration means that these waste products are less diluted, which is why urine becomes darker as dehydration progresses. This makes urine a useful and straightforward method for monitoring hydration state by the individual. The following are important:

- an individual should attempt to produce urine that is equivalent to colours 1, 2 or 3 on the ‘urine chart’ (Appendix II), or pale yellow
- do not judge urine colour within a few hours of taking vitamin supplements, as unused vitamins may turn the urine a more intense colour
- try to check urine at similar times of the day
- the first specimen of urine produced for a test is often more concentrated than later specimens, so the second should be used for judging colour where possible
- frequency and volume are also good indicators of hydration state – more frequent and greater volumes indicate a better hydration state
- alcohol is a strong diuretic, which means it causes the body to release water that may be clear or pale coloured at the time. However, it is the loss of this water that causes dehydration, and hence produces darker coloured urine later or the next day
- where possible, the urine sample should be produced into a clear container to be judged, rather than into the lavatory where it will be diluted
Correct treatment
If a firefighter is suffering from heat injury and the treatment administered is incorrect (e.g. bending the casualty over and putting their head under a water pump), the problem may be worsened. Consult Table 12.1 for correct treatment methods.

Fluid intake regime - rationale
Incorporating an effective fluid intake regime is essential to combat the effects of heat strain and dehydration. Such a regime should be implemented during operational and training work. To minimise the risk of heat injury, water losses (due to sweating) should be replaced at a rate equal to the sweat rate. However, during exercise humans typically do not drink as much water as they lose in sweat, and at best voluntary drinking only replaces about two-thirds of that lost. It is common for individuals to dehydrate by 2-6% of their body weight during exercise in the heat despite the availability of adequate amounts of fluid. Thirst is not a good indicator of the need to intake fluids, and therefore firefighters need to rely on strategies such as a drinking regime or measuring body weight loss (where possible), especially during prolonged periods of work. Following fluid volume depletion, individuals tend to ingest more fluid and retain a higher percentage of that fluid when electrolyte (salt) deficits are replaced. In fact, complete restoration of body fluids cannot take place without electrolyte replacement in food or beverages.

Drinking rates
During physical work, many people report feelings of stomach fullness and discomfort while attempting to consume fluid at a rate equal to their sweat rate, especially when this is in excess of 1 litre per hour. However, this response is individual and some will be able to consume more than others will before experiencing discomfort. Therefore, individuals should be encouraged to consume the maximal amount of fluids during work / exercise that can be tolerated without experiencing stomach discomfort, up to a rate equal to that lost from sweating.

Drink volume
Once fluid has been ingested, it passes into the stomach and then the intestine. Water is absorbed from the intestine into the blood. Therefore, the rate at which fluid balance will be restored is determined by the rate at which fluid is emptied from the
stomach and absorbed from the intestine into the blood. Just because fluid has been swallowed, does not mean to say that it is immediately useful to the body. This is why advance preparation is important. The most important factor influencing the rate of stomach emptying is the volume of fluid – larger volumes encourage absorption. The addition of carbohydrates to a fluid replacement solution can enhance intestinal absorption (concentration 4-8%). However, the rate of emptying is slowed proportionately with increasing carbohydrate concentration above 8%. When the volume of fluid in the stomach is maintained at about 600 ml, most individuals can empty more than 1 litre per hour from their stomach.

To avoid or delay the detrimental effects of dehydration during work and / or heat exposure, benefit can be gained by consuming fluid prior to the work period. Water ingested 1 hour before physical work will enhance thermoregulation and lower heart rate during the work. However, this may increase urine volume by up to four times that normally produced, which would prove impractical during firefighting tasks. Therefore, the consumption of 400-600 ml of water 2 hours before physical work / heat exposure will allow the body time to regulate fluid volume prior to the start of work.

During prolonged work, frequent consumption (every 15-20 mins) of moderate (150 ml) to large (300 ml) volumes will provide a high stomach volume to aid in fluid absorption. However, since stomach emptying rates and tolerance to large volumes differ between people, individuals should learn personal tolerance limits for different activities and durations.

It has been found that individuals who consume a volume equivalent to or less than their sweat loss cannot return to normal hydration levels. Drinking 1½-2 times the volume lost as sweat is necessary to return body fluids to normally hydrated levels. If an individual has no idea of the volume of sweat lost during physical work / heat exposure, in addition to drinking throughout, they should consume at least 1 litre of fluid in the first 30 minutes following the work. Fluid replacement should continue until urine colour returns to colours 1, 2 or 3 on the urine colour chart (Appendix II). Any excess body water will be removed by urine production.
Drink temperature

Enhancing palatability of fluids is one way to encourage drinking so that intake is better matched to sweat loss. Generally, the most preferred water temperature is about 5°C following physical work. However, when water is consumed in large quantities, a temperature of about 15-20°C may be preferred.

Drink flavouring

Another factor which influences water palatability is drink flavouring and / or sweetening. People tend to consume more water voluntarily if it is flavoured and / or sweetened (artificially or with sugar).

Electrolyte replacement

The salt lost in sweat must be replaced to allow proper restoration of body fluid levels. However, since the concentration of salt in sweat is far less than the amount of salt within our body fluids, and our diets tend to contain more salt than our body needs, the lost sodium can generally be accomplished by normal dietary intake. Hence, regular meals are of importance. If the addition of salt to fluids enhances palatability, and therefore encourages drinking, then its presence may be justified. Drinks such as squash contain a small amount of salt for this reason. If sweating during a protracted incident takes place for over 4-5 hours, it is likely that extra salt supplementation within drinks will be necessary to replace that lost in sweat.

Carbohydrate replacement

For sweating durations of more than 1 hour, carbohydrates should be added to fluid replacement drinks to maintain blood glucose concentration and delay the onset of fatigue. This can be done by consuming 600-1200 ml of fluid per hour where the concentration of carbohydrates is 4-8%. This allows fluid and carbohydrate requirements to be met simultaneously during prolonged work. The use of glucose and sucrose are equally effective, but fructose should not be the predominant carbohydrate, as it is converted slowly to blood glucose. It is not thought necessary to consume anything other than water for sweating durations of less than 1 hour.
Availability

Fluids should be made as available as possible to encourage drinking. During training in firehouses, fluids should be placed in as many relevant locations as possible, such as the debrief room, student waiting area near the firehouse, BA maintenance room, firehouse control room (for instructors) etc. A range of fluids, prepared according to the information in this booklet should be available. Drinking bottles enhance drinking, as they can be carried around with an individual, but other containers should also be provided.

Provision should be made to supply firefighters with appropriate fluids during operational incidents, especially protracted incidents. They should not have to seek fluid replacement, it should be immediately available at all times to encourage regular drinking.

Container hygiene

Poor hygiene when using drinking bottles (or similar), particularly with sugar based drinks, results in bacterial growth with subsequent stomach upsets and diarrhoea. Proper cleaning and sterilisation of containers is necessary, even if a container is only used by one person.

Water safety

Only water from known safe sources should be consumed, which excludes drinking from hydrants and rivers. The logistical problems of providing a number of firefighters with adequate fluids either during training or at an incident should be taken into account. Individual drinking bottles generally hold 1 litre, which is only enough for the first hour of physical activity in the heat. Further supplies are necessary.

Food consumption

Food intake should be encouraged (where it will not result in stomach discomfort due to activity), both during physical work and afterwards. This is because people tend to consume more fluids when eating than when not eating, and also, the electrolytes in food enhance fluid absorption and retention in the body.
**Fluids to avoid**

The following should be avoided as rehydration fluids:

- Caffeine (tea, coffee, coke, hot chocolate) – caffeine is a diuretic which means it makes your body lose water
- Carbonated drinks – fizzy drinks create a feeling of fullness before a person has consumed enough fluid
- Alcohol – alcohol is a very strong diuretic, and the consumption of large quantities prior to physical work and/or heat exposure increase the likelihood of severe dehydration problems
- Oral rehydration solutions – these contain very high electrolyte concentrations and are designed to treat acute diarrhoea
- Carbohydrate-electrolyte beverage concentrations greater than 8% - these can exaggerate the problems of dehydration

**Fluids that are advisable to drink**

- Water
- Squash
- Juice
- Milk (if desired)
- Carbohydrate-electrolyte beverage concentrations less than 8% (when necessary)
12.2.7 Summary of precautions for physical work in the heat

Ideally, drinks consumed to prepare you for a physical work and heat exposure should fulfil as many of the following criteria as possible. The reasoning behind this is so that you are encouraged to drink because it tastes nice, and also, that when you do, the fluid is absorbed as quickly as possible into your body.

- available  
- flavoured  
- cool  
- palatable  
- safe  
- slightly salted  
- provide an energy source where appropriate

It is very important to consume fluids before and during, as well as after a heat exposure. This is because your body cannot provide water for sweat if you have not given it some extra fluid in the first place! The following are some guidelines on how much to drink and how often:

- 500 ml (½ litre) 2 hours before physical work / heat exposure
- 300 ml 15-20 minutes before physical work / heat exposure
- 200 ml every 20 minutes physical work / heat exposure (or the maximum that can be tolerated without discomfort)
- 1000 ml (1 litre) within 30 minutes of finishing the work
- Further drinking until urine returns to colours 1, 2 or 3 on the urine colour chart

If you are training, you will always have the chance to prepare and be well hydrated. Operationally, you can still attempt to consume a glass of water or squash every 20-30 minutes in case you do receive a call. During both training and operational work there should always be appropriate fluids available in large quantities.

Employ as many of the following as possible during physical work and or heat exposure:
- controlled SCBA work
- replacement of soaked clothes underneath firekit
- active cooling measures (eg. wrist in water and fan cooling)
- work / rest schedules
- temperature / weight loss / urine monitoring
- increased fitness levels  
- acclimatisation
Glossary

Acclimatisation - reduction in heat strain due to increased ability to cope with exercise / heat stress
Cardiac output - the volume of blood pumped per minute by the heart (heart rate x stroke volume)
Diuretic - an agent that promotes the excretion of urine, thereby lowering blood volume and pressure
Electrolytes - ions and molecules present in the plasma that are able carry an electric current - when produced in sweat, they are often referred to as salt
Haemoconcentration - increased ratio of red blood cells to total blood volume (due to water loss)
Plasma - the fluid portion of circulating blood
PPE - personal protective equipment
Renal function - kidney function
Thermoregulation - the body's ability to maintain 'normal' body temperature
Vasodilation - widening of the blood vessels to increase blood flow to the skin
VO2 max - a person's maximal work capacity (cardiac output x oxygen uptake necessary to supply oxygen to the muscles)

12.3 Summary

This chapter aimed to provide knowledge on hydration issues (from existing sources and work carried out in this thesis) in a format that would enable both fire training instructors to give guidance to their students, and general firefighters to access straightforward information on remaining well-hydrated during their work.

12.4 Summary of Part IV

The main findings of this section of the thesis are as follows:

- In Chapter 10 an in-depth discussion of the physiology and regulation of the body fluids took place. Some illustrated examples were then presented to demonstrate how this understanding of the concepts of body water can be applied in order to provide practical guidance.

- Although a good understanding of any system may have been gained (ie. body water) and sound advice could be provided, practical problems may exist in implementing such advice. This issue was addressed in Chapter 11, using the job of a fire training instructor, where issues such as the placement of available fluid
were identified. Attending to such issues lessens the likelihood that fluid intake guidelines will not be followed.

- Chapter 12 aimed to provide a guidance document on the causes, consequences and preventative measures involved in dehydration and heat strain, in a format that would allow fire training instructors to take advice themselves and also provide it to recruits. It could also be used as a quick reference source by firefighters in general, as a one page summary is provided at the end. The guidance document draws together existing information, experimental data, theory and practical considerations to provide a usable method for controlling hydration state in the hot working environments firefighters are exposed to.
Part V

Discussion

and

Conclusions
Chapter 13
Chapter 13

DISCUSSION

13.1 Introduction
The aims of this thesis were as follows: 1) To review current literature and available guidelines on the factors affecting dehydration and rehydration, and study the influence of acclimation; 2) To develop practical and accurate methods of measuring hydration state, which could be used in laboratory work, and ultimately in field-based work; 3) To determine the extent of hydration problems during firefighter training (for instructors and recruits), as several Fire Brigades had expressed concern in this area; 4) To implement an effective and practical fluid intake regime into firefighter training; and 5) To provide guidance for firefighter recruits and instructors in the form of quick reference information, and where required, more in-depth analyses of body water changes.

13.2 Aim 1: To review current literature and available guidelines on the factors affecting dehydration and rehydration, and study the influence of acclimation

For many people, work in the heat is an issue, as high sweat rates are required to regulate core temperature (Sawka & Wegner, 1988). Such high sweat rates can lead to body water deficits, which have been well-documented to produce elevated core temperatures and heart rates during physical work in the heat (Adolph, 1947; Eichna et al, 1945). Chapter 1 detailed the environment, clothing and activity to be the main causes of dehydration, and how, either singly or in combination, these factors could cause significant hydration problems for an individual. If fluid intake is present, some of these effects may be attenuated; however, voluntary dehydration (Greenleaf, 1992) during work in the heat was also shown to be a contributing factor to hydration problems.

The effects of dehydration can be classed according the percentage of body weight lost through sweating (Greenleaf et al, 1982), and range from impaired exercise
thermoregulation at about 1% of body weight (water) loss, leading to likely collapse at about 7% of body weight, when exercise and heat are combined. Dehydration also affects physical performance: in combination with a hot environment, it is most apparent in tasks requiring stamina; with a body weight loss of 4%, there may be a decrease of almost 50% in physical work capacity and a loss of almost 30% of aerobic power (Craig & Cummings, 1966), and therefore maximal performance.

Although there is little documented evidence on the effects of dehydration on mental performance, there is much on the effects of heat stress, and since the elevation of core temperature is common to both, it is likely that they are similar (Pepler, 1964). Generally, it seems that simple reaction time, speed and accuracy of response in complex reaction tasks, vigilance (Grether, 1973), tracking tasks (Ramsey, 1975), and mental reasoning (above 38°C) (Lampietro, 1965) are all reduced above effective temperatures of about 30°C.

When the body has experienced a high enough water deficit, sweating will either decrease or cease, causing a further increase in core temperature. It is this excessive heat storage that leads to heat illness, the effects of which are progressive if not treated, and the worst type of which is heat stroke, that may be fatal.

Chapter 1 also addressed various methods of reducing the effects of dehydration during work in the heat. There is a wealth of information in the literature on rehydration strategies, including drink timing, volume, content (carbohydrate / electrolyte) and palatability, which were summarised in Chapter 1. Another method of reducing the effect of dehydration and heat strain whilst working in a hot environment is acclimatisation, and this subject was addressed in detail in Chapter 2. A small-scale, in-depth study was carried out in order to determine whether the benefits of acclimation could be accrued over a relatively short period, whilst consuming a diet containing a moderate amount of salt. This was found to be the case, and allowed guidelines to be provided later in the thesis regarding the benefits of acclimation in hot working environments (reduced physiological strain) and potential drawbacks (greater sweat production in a given time increases the likelihood of dehydration occurring, unless additional fluid is consumed).
13.3 Aim 2: To develop practical and accurate methods of measuring hydration state, which could be used in laboratory work, and ultimately in field-based work
Part II of the thesis aimed to form a battery of hydration tests that were both practical and accurate (reliable, sensitive and valid). These were intended for use in laboratory work, and ultimately in field-based work. Chapter 3 addressed the issue of thirst and concluded that it alone is not a sufficient indicator of the need to consume fluid, and therefore of hydration level. Voluntary dehydration is one of the major reasons for this. Due to the unsuitability of thirst as a measure of hydration state, Chapter 4 went on to assess the practicality and accuracy of a large range of physiological tests, including urinary, haematological and sweat variables. The study found that urinary measures of osmolality, specific gravity and colour were all accurate methods of assessing hydration state. Urine colour is an extremely practical measure to take, and can actually be used by workers to monitor their own hydration state. Urine specific gravity requires a little more equipment and practice, yet is still reasonably easy to measure, whereas urine osmolality requires a laboratory setting and analysing expertise.

The bio-impedance analysis (BIA) technique has become popular over recent years as a method for analysing the volume of body fluid compartments. In Chapter 5, a small study was carried out to determine how useful this technique would be in the work of this thesis. The chapter concluded that although the technique seemed accurate and feasible in a non-sweating, normally hydrated, sedate subject, it was not when a subject was hot, physically active, sweating, and therefore highly likely to be hypohydrated. Therefore, further work is thought necessary to determine to reliability, sensitivity and validity of the BIA technique for this type of application and it was not further pursued in this thesis.

13.4 Aim 3: To determine the extent of hydration problems during firefighter training (for instructors and recruits)
Several Fire Brigades expressed concern that firefighters (instructors and recruits) were experiencing dehydration and hence heat strain problems during hot fire training. Chapter 6 reviewed the training process and conditions in firehouses during
firefighter training, and also identified possible contributing factors, such as PPE and activity level, to dehydration and heat strain. It was determined that the fire training instructors and the recruits carried out different regimes during a day of hot fire training, and therefore may experience different problems with regard to dehydration and heat strain.

An experiment was carried out in Chapter 7 to measure the hydration state of recruits during hot fire training. This chapter concluded that firefighter recruits do not have a significant dehydration problem during this time, principally because they are only exposed to hot conditions for a very limited time.

Subsequently, an experiment was carried out to monitor the hydration state of fire training instructors during hot fire training (Chapter 8). This study recorded excessive rises in core temperature, negative water balance and voluntary dehydration. It was concluded that these could in part be attributed to insufficient fluid intake as well as the heat exposure.

13.5 Aim 4: To implement an effective and practical fluid intake regime into firefighter training

In order to implement an effective and practical fluid intake regime during firefighter training, two experiments were carried out. Firstly, the work of training instructors was simulated in a laboratory-based experiment in hot conditions (Chapter 9). During this time, the fire training instructors followed three different fluid intake regimes: ad libitum drinking, and two controlled drinking regimes. The study found that the controlled drinking regimes attenuated rises in aural and skin temperatures, heart rate, total ventilation, and subjective measures of thermal sensation, thirst, dizziness and light-headedness, compared to ad libitum drinking.

Once the effectiveness of a controlled drinking regime was established, the practical issues of implementing one into the workplace, such as during firefighter training, were addressed (Chapter 11). A study involving many brigades was carried out, whereby recruits and instructors attempted to follow the drinking regime throughout firefighter training. The main outcomes were that consideration should be given to
the placement of both fluids and intake guidelines. Each should be placed in several locations around the training area. Since problems of inconvenience and lack of time are experienced throughout such days of training, fluids should be made as readily available as possible.

13.6 Aim 5: To provide guidance for firefighter recruits and instructors in the form of quick reference information, and where required, more in-depth analyses of body water changes

The implementation of such a fluid intake regime would be of greater benefit when used in tandem with education regarding work in the heat. Therefore, information was provided both in the form of quick reference information, and more in-depth analyses of body water changes. Chapter 10 provided detail on the changes that take place in the body when water and electrolytes are removed or added, and provided some worked example of questions commonly asked by people who work in the heat. Chapter 12 was produced in the form of a guidance document on the effects of dehydration and heat strain, and how to reduce those effects. It was tailored to the needs of training for the Fire Service, but could be amended for any workplace.
Chapter 14
Chapter 14

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

14.1 Conclusions

- When monitoring the hydration state of people who work in the heat, the urinary indices of osmolality, specific gravity and colour (and volume to a lesser extent) provide a combination of accuracy and practicality. However, results were not entirely consistent over all experiments. In addition, thirst cannot be relied upon as a method for accurately regulating fluid intake.

- In the studies detailed in this thesis, firefighter recruits did not experience significant dehydration problems during hot fire training, whereas fire training instructors did. It should be noted that these conclusions are limited to those conditions studied.

- A controlled fluid intake regime provided attenuation in physiological strain compared to *ad libitum* drinking during simulated fire instructor work in hot conditions.

- An effective fluid intake regime can be successfully implemented into firefighter training, so long as sufficient provision is made in terms of time and availability of fluids.

- To accompany the fluid intake regime, a guidance document on the effects of dehydration and heat strain, and how to reduce those effects has been produced. In addition, more in-depth analysis of body water changes has been provided.
14.2 Recommendations for further work

- In the case of firefighter training, a follow up study to determine the long-term success of a fluid intake regime would be sensible. This would present the opportunity to tackle any practical problems that may have developed or gone unnoticed until now.

- Assessing the incidence of dehydration during operational firefighting has not been addressed to date. This would be problematic in terms of interference with work, but nevertheless of importance when considering the health and safety of firefighters attending protracted incidents, which can in some cases last several days (it is unlikely that any firefighter would attend for that whole length of time, however).

- Taking into account the two previous recommendations, a further one would be to implement an effective system of education and monitoring into an organisation (whether it be the Fire Service or not) at all levels, and as part of initial training. This may help to ensure a more proactive than reactive approach to hydration in hot working conditions.

- The bio-electrical impedance analysis (BIA) technique examined in Chapter 5 clearly has potential as a tool for determining the extent of body water changes. However, further work is necessary to overcome the difficulties experienced, which may have been due to the hot, sweating state of the subject, calibration issues, or another factor. This would be necessary in order to establish the reliability, sensitivity and validity of the technique.

- In order to provide practical methods for urine analysis, for example during an occupational health study or by fire training instructors running a recruit course, it may be possible to develop a urine analysis kit. This may comprise of equipment to measure urine specific gravity, volume and colour, all of which require little training. This should be accompanied by appropriate instructions and target values for each of the measures.


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Glossary
GLOSSARY

acclimation - reduction in heat strain due to increased ability to cope with exercise / heat stress, resulting from artificial exposure to heat

acclimatisation - reduction in heat strain due to increased ability to cope with exercise / heat stress, resulting from natural exposure to heat

acute dehydration - being dehydrated for less than 24 hours

aldosterone - a mineralocorticoid produced by the adrenal cortex that brings about sodium and water reabsorption and potassium excretion

alliesthesia - a stimulus engendered by drinking that depends on the internal status of the subject and characteristics of the fluid, i.e. odour, clarity, palatability and temperature

angiotensin - either of two forms of protein associated with the regulation of blood pressure. Angiotensin I is produced by the action of renin on angiotensinogen and is converted by the action of a plasma enzyme into angiotensin II, which stimulates aldosterone secretion by the adrenal cortex

antidiuretic hormone (ADH) - also known as 'vasopressin'. A hormone produced by the hypothalamus and secreted by the posterior pituitary gland; it acts on the kidneys to promote water reabsorption

atrial natriuretic factor (ANF) - peptide hormone, produced by the atria of the heart in response to stretching, that inhibits aldosterone production and thus lowers blood pressure

cardiac output (Q) - the volume of blood pumped per minute by the heart (stroke volume [SV]) x (heart rate [HR])

chronic dehydration - being dehydrated for MORE than 24 hours

dehydration - the dynamic loss of body water, or the transition from euhydration to hypohydration, or negative water balance

diuretic - a chemical that inhibits sodium reabsorption, reduces antidiuretic hormone concentration and increases urine volume by inhibiting facultative reabsorption of water. It thereby reduces blood volume and pressure

electrolytes - ions and molecules present in the plasma that are able to carry an electric current - when produced in sweat, they are often referred to as salt

euhydratation - normal body water content

ergogenic aids - pharmacological and/or nutritional substances, and physiological procedures or strategies which induce an improvement of one or more physical fitness components. EA are not only considered to be effective if they improve physical performance, but also if their effect causes a delay, reduction or avoidance of decrements in physical work capacity caused by various environments (e.g. heat, cold, altitude)

extracellular fluid (ECF) - fluid outside body cells, such as interstitial fluid and plasma

fluid retention - this occurs with excess salt retention, although the ECF is still isotonic because the increase in salt is matched by an increase in water

glomerular filtration rate (GFR) - the total volume of fluid that enters all the glomerular (Bowman's) capsules of the kidneys in 1 minute (about 125 ml/min)
haematocrit - the percentage of blood made up of red blood cells, usually calculated by centrifuging a blood sample in a graduated tube and then reading off the volume of red blood cells and total blood.

haemoconcentration – increased ratio of red blood cells to total blood volume (due to water loss)

haemoglobin - a substance in erythrocytes consisting of the protein globin and the iron-containing red pigment heme. It constitutes about 33% of the cell volume, and is involved in the transport of oxygen and carbon dioxide.

heat exhaustion - is caused by dehydration. The symptoms include chills, light-headedness, dizziness, headache and nausea. The body temperature is usually between 37.7 - 38.8°C and profuse sweating is evident.

heat oedema - associated with hypohydration and electrolyte imbalances.

heat stroke - this is caused by a sudden failure of the thermoregulatory system of the body. Heat stroke may be fatal. It is often considered to lie on a continuum with heat exhaustion. It initially appears similar to heat exhaustion, but may rapidly progress to manifest more serious neurological symptoms: disorientation, loss of consciousness and seizures (fits / epilepsy). The body temperature may be higher than 40°C. Sweating if often absent but the skin may be moist from earlier perspiration. The pulse is usually faster than 160 bpm, and the blood pressure may be low. Kidney damage (acute nephropathy) occurs in about 35% of cases. Rhabdomyolysis (muscle breakdown) and the myoglobinuria (excretion of muscle breakdown products) contributes to the kidney injury. Liver damage is also evident when liver enzymes are measured following heat stroke.

hyperglycemia - abnormally increased concentration of glucose in the blood.

hyperkalemia - abnormally high concentration of potassium in the blood.

hypertonic - a solution with a greater solute concentration (osmolarity) and thus a greater osmotic pressure than plasma.

hypohydration - body water deficit.

hypotonic - a solution with a lesser solute concentration and thus a lesser osmotic pressure than plasma.

hypovolemia - decreased blood volume (therefore, a decrease in blood pressure).

insensible water loss - body water loss from the lungs and non-sweating skin (loss without a person’s awareness).

interstitial fluid - the fluid that lies in the spaces between the cells.

intracellular fluid - fluid located within the cells.

isotonic - an osmolarity equal to the normal osmolarity of the body fluids.

lymph - fluid being returned from the interstitial fluid to the plasma by means of the lymphatic system.

metabolic water - produced during cellular metabolism, when chemical reactions in the cells convert food and oxygen into energy, producing CO2 and H2O in the process.

mets (metabolic unit) - one met equals the VO2 at rest. The estimate of the value of one met is 3.5 ml O2/kg/min. Conversion of VO2 measurements may be obtained by dividing the value of the VO2 in ml.
of oxygen/kg/min by the value of one met, or 3.5. For example, a VO₂ measurement of 35 ml O₂/kg/min is equivalent to an output of 10 mets.

**mineralocorticoids** - a group of hormones of the adrenal cortex

**osmolality** - of a fluid is a measure of the concentration of the individual solute particles dissolved in it

**overhydration** - when excess free water (water not accompanied by comparable solutes) is present

**oxygen uptake** - (cardiac output) x (arterial-venous oxygen difference)

**plasma** - the fluid portion of the blood (not the formed elements)

**PPE** - personal protective equipment

**prescriptive zone** - the range of external temperatures over which the deep body temperature can be stabilised during exercise

**reactive hypoglycaemia** - low blood sugar as a result of ingesting high concentrations of sugar. In a non-exercising body, eating high concentrations of sugar causes insulin to be released, which stores glucose, removing it from the bloodstream. If the body begins exercising then the blood sugar falls very quickly and may go well below resting levels. Symptoms: light-headedness, lack of energy & motivation, and possibly nausea

**renal function** - kidney function

**salt depletion dehydration** - negative salt balance (with comparable water loss)

**syncope** - fainting (causes mild cardiovascular and CNS disturbances)

**thermoregulation** - the body's ability to maintain 'normal' body temperature

**transcellular fluid** - a number of small specialised fluid volumes, all of which are secreted by specific cells into a particular body cavity to perform some specialised function eg. cerebrospinal fluid, synovial fluid, pericardial fluid

**vasodilation** - widening of the blood vessels to increase blood flow to the skin

**VO₂ max** - the maximum amount of oxygen that can be consumed by the body per unit time during heavy exercise (cardiac output x oxygen uptake necessary to supply oxygen to the muscles)

**voluntary dehydration** - creating a body water deficit, despite the availability of adequate fluids with which to rehydrate the body

**water intoxication** - the condition of overhydration, hypotonicity, and cellular swelling resulting from excess free water retention (not to be confused with fluid retention that occurs with excess salt retention)

**WBGT** - Wet bulb globe temperature = 0.7 x Twb + 0.2 x Te + 0.1 x Tdb

From this formula, it is evident that the humidity is valued as the major determinant of heat stress, as it is weighted at 70% of the value. Below a WBGT value of 18°C, the risk of heat injury is small. Above a WBGT value of 28°C, there is a significant chance of heat stress occurring whilst working in the heat. Higher humidity levels will decrease the evaporation of perspiration, and thereby inhibit one of the primary means by which the body can cool itself.
Appendix I

Health Screen Questionnaire
It is important that volunteers participating in research studies are currently in good health and have had no significant medical problems in the past. This is to ensure (i) their own continuing well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

Please complete this brief questionnaire to confirm fitness to participate:
If YES to any question, please describe briefly in the spaces provided (eg to confirm problem was/is short-lived, insignificant or well controlled.)

1 At present, do you have any health problem for which you are:
(Please tick as appropriate)
(a) on medication, prescribed or otherwise
Yes [ ] No [ ]
(b) attending your general practitioner
Yes [ ] No [ ]
(c) on a hospital waiting list
Yes [ ] No [ ]

Optional questions for female participants
(Please tick as appropriate)
(a) are your periods normal/regular?
Yes [ ] No [ ]
(b) are you on "the pill"?
Yes [ ] No [ ]
(c) could you be pregnant?
Yes [ ] No [ ]
(d) are you taking hormone replacement therapy (HRT)?
Yes [ ] No [ ]

Thank you for your co-operation!

Declaration Of Consent

I, .................................................. hereby volunteer to be an experimenter subject to thermal experiments during the period of / on .................................................. 199 ....

My replies to the above questions are correct to the best of my belief and I understand that they will be treated with the strictest confidence by the experimenter. The purp of the experiment has been explained by the experimenter and I understand what w be required of me.

I understand that I may withdraw from the experiment at any time and that I am un-obligation to give reasons for withdrawal or attend again for experimentation. I also understand that the experimenter is free to withdraw me from experimentation any time.

I undertake to obey the laboratory regulations and the instructions of the experimenter regarding safety, subject only to my right to withdraw as declared above.

Signature of Subject .............................................. Date ...............

Signature of Experimenter ......................................... Date ............
TEXT BOUND INTO THE SPINE
Appendix II

Urine Colour Chart
Urine Colour Chart

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2
3
4
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