Individual Heat Stress Response

ISBN: *90-9010979-X*

Cover design: *George Havenith / Walter van Dijk: false colour infra-red image of TNO colleagues.*

Printer: *Ponsen en Looijen BV*

Individual Heat Stress Response

Een wetenschappelijke proeve
op het gebied van de Medische Wetenschappen

Proefschrift

ter verkrijging van de graad van doctor
aan de Katholieke Universiteit Nijmegen,
volgens besluit van het College van Decanen in het
openbaar te verdedigen op dinsdag 4 November 1997
des namiddags om 3:30 uur precies

door

George Havenith

geboren op 25 september 1956
te Heerlen

- Promotor: prof. dr. R.A. Binkhorst
- Co-promotor: dr. W.A. Lotens (TNO-TM)

- Manuscriptcommissie: prof. dr. A. van Oosterom, voorzitter
  dr. M.A. van 't Hof
  prof. dr. H. Kuipers (UM)

The research presented in this thesis was performed at the TNO Human Factors Research Institute, Soesterberg, The Netherlands and at Noll, physiological Research Center, University Park, PA, USA.
The research was financed by the Netherlands Council for Defence Research.

CONTENTS

List of abbreviations ii

1 Introduction 1
- 1.1 General introduction
- 1.2 Background
- 1.3 Methodology
- 1.4 Outline

2 Age predicts cardiovascular, but not thermoregulatory, responses to humid heat stress 23

3 The relative influence of body characteristics on humid heat stress response 45

4 The influence of individual characteristics on physiological response during relative load exercise in different climates 67

5 The relevance of individual characteristics for human heat stress response is dependent on work intensity and climate type 81

6 Thermal modelling of individual characteristics 107
- 6.1 Introduction
- 6.2 The necessity of individualization
- 6.3 The model
- 6.4 Validation
- 6.5 Conclusion

7 Example simulations 143

8 Summary and suggestions for future research 155

9 Samenvatting en aanbevelingen voor verder onderzoek 163

Program listing, Appendix 1 171

Bibliography, Appendix 2 179

Acknowledgements 185

Curriculum Vitae 189

Abbreviations

α	= relative size of skin compartment
ABS	= absolute workload (60W)
Acclim	= acclimation
ACSM	= American college of sports medicine
ACTIV	= daily activity score
A_D	= body surface area
A_D/mass	= body surface area to mass ratio
ASHRAE	= American Society of Heating Refrigerating and Air Conditioning Engineers
BF	= blood flow
c_b	= specific heat of body tissue
CEN	= Centre Européen de Normalisation
CO	= cool climate (21 °C, 50% r.h.)
D_{body}	= density of body tissue
diast	= diastolic blood pressure
DRY	= dry heat loss (radiative+convective+conductive)
ET	= Effective Temperature
EVAP	= evaporative heat loss
%fat	= body fat percentage
FBF	= forearm blood flow
FVC	= forearm vascular conductance
GXT	= graded exercise test
Hcap	= heat capacity
HD	= hot dry climate (45°C, 20% r.h.)
HR	= heart rate
HST	= heat stress test
I_{cl}	= clothing insulation
ISO	= International Standardization Organization
LBM	= lean body mass
MAP	= mean arterial pressure
mass	= body mass
MSBF	= maximal skin blood flow
MSR	= maximal sweat rate
n	= number of datapoints (subjects)
P_a	= ambient water vapour pressure
p	= statistical significance level
r	= correlation coefficient
r^2	= explained variance
rad	= added radiation (above normal at T_a)
RC	= regression coefficient
R_e	= clothing vapour resistance
Ref	= reference temperature (setpoint/threshold)
REL	= workload relative to individual $\dot{V}O_{2\,max}$
RESP	= respiratory heat exchange
r.h.	= relative humidity
SD	= standard deviation

SE = standard error
SF = sum of 7 skinfolds
shiver = shivering metabolic rate
sk = skin
SKBF = skin blood flow
STORE = body heat storage
sw = sweating
syst = systolic blood pressure
T_a = ambient temperature
T_{body} = mean body temperature
T_{co} = body core temperature
T_{oes} = oesophageal temperature
T_{re} = rectal temperature
T_{sk} = mean skin temperature
v = wind speed
$\dot{V}O_2$ = minute oxygen consumption
$\dot{V}O_{2\,max}$ = maximal oxygen uptake
$\dot{V}O_{2\,max}$ ff = maximal oxygen uptake per kg fat free body mass
$\%\dot{V}O_{2\,max}$ = work load as % of maximal oxygen uptake
WBGT = wet bulb globe temperature
WBT = Wet Bulb Temperature
WH = warm humid climate (35°C, 80% r.h.)

1

Introduction

Chapter 1

INTRODUCTION

1.1 General introduction

The aim of this thesis is to contribute to the improvement of the quality of heat strain prediction in healthy humans. Heat strain prediction is possible using thermal indices or models. In this prediction several parameters are of importance: the type of index or model, the climate, the task which has to be performed, the clothing worn, and the characteristics of the person involved. These parameters will be described below. The characteristics of the individual have hardly been incorporated in heat stress modelling. The emphasis of this thesis will therefore be the role of individual characteristics in heat stress response.

1.1.1 Thermal indices and models

Empirical indices

Heat strain determination and prediction is a subject which importance was recognized in industry early this century, when people began to pay more attention to work conditions. This interest, also coming from the indoor-climate control industry, led to first attempts to define heat stress by a single index value, like the Wet Bulb Temperature (WBT, Haldane, 1905) or the Effective Temperature (ET, Houghton and Yaglou, 1923). Research on this subject was boosted when military interest in the subject increased. In the United States, with the involvement in World War II, recruits from all parts of the US were trained in the Southern States, with their warm, humid summers. The high incidence of heat exhaustion and heat stroke during military training pointed out the need for instruments or methods to determine the risks involved with exercise in such stressful climates. Adolph (1947), published a book reviewing a number of studies performed with military personnel during and after the war, dealing with risks of heat exposure and ways to reduce these risks. Schickele (1947) published data on the relation of the occurrence of heat stroke with climatic factors. Later these findings were incorporated in the design of a measuring device which was used to determine a heat stress index, the Wet Bulb Globe Temperature (WBGT[1], Yaglou and Minard; 1957). This device allowed management of training sessions and work duration in relation to the climatic stress. Individual variations in

[1]Wet Bulb Globe Temperature: Climate index, which is based on measurement of natural wet bulb temperature, air temperature and globe temperature, indicating the level of heat stress in a single value. Climates with equal WBGT are supposed to induce equal stress on a subject.

response were not accounted for by these indices. Only in the interpretation, different tables were e.g. used for acclimated and non-acclimated subjects

Analytical indices

The applicability of all these indices however, as their relation with heat strain was determined empirically and only based on climatic parameters, was limited to situations which were studied before. Especially changes in metabolic rate or in clothing, produced discrepancies between observed and predicted strain. This led to the development of analytical indices, dealing with actual heat and mass transfer between human skin and environment. Two examples of such indices, which really are based on the human heat balance equation[2], are the Heat Stress Index (Belding and Hatch, 1955) and the Required Sweat Rate Index (ISO 7933, 1989). These improved strain prediction, and widened the range of applicability of indices. Some basic individual characteristics related to the anthropometry and acclimation were introduced in some of these models, but their impact was hardly validated.

Physiological models

Around 1970, when substantial data on thermoregulatory control functions became available in the literature, and with the increasing availability of computers, the development of physiological simulation models started. These models combined physics of internal and external heat flow with internal body temperature regulation. The most well known physiological models of human thermoregulation were initiated by research for space travel. Stolwijk (1971) published a 25 compartment thermoregulatory model, incorporating control functions for blood flow, sweating and metabolism for use by NASA. He was followed by many other authors who published relatively simple (Gagge et al., 1971, 1986) to more complex (Wissler, 1964, 1982; Werner, 1989; Werner and Webb, 1993) physiological models. These models all allowed the introduction of anthropometric data, and some acclimation, but these parameters were hardly validated for work in the heat.

Clothing

Once the physiological part of these models was developed, researchers started to improve the description of the interface between man and environment in these models: the air layers at the skin, at and within the clothing, and the clothing itself. Basic data for this purpose were gathered in the 1940-1960 period already (for a historical review see Gagge, 1983). Originally, people worked with static data on

---

[2]The heat balance equation defines the balance of the rates of heat production and heat losses. Rates of metabolic heat production at thermal equilibrium equal the sum of the rates of external work, respiratory-, convective-, radiative- and evaporative heat gains or losses. If not, this implies that heat is stored in the body. Positive storage leads to body temperature increase, negative storage to a decrease.

clothing and air layers. Next, correction factors for changes in clothing and air layer heat and vapour resistance due to movement, posture and wind were determined (Olesen et al., 1982; Nielsen et al., 1985; Havenith et al., 1990a,b; Danielsson, 1993) and incorporated into models (Lotens and Havenith, 1991). After extensive study of the different avenues of heat and mass transfer in clothing, Lotens (1993) combined a model of these processes with the thermoregulatory model by Gagge et al., (1986) and showed that this model improved heat strain prediction drastically in a number of conditions.

Individual subjects

The models which are presently available give acceptable predictions of the average group response to heat stress (Lotens, 1993). A source of error in the predictions emerges when reactions of individual subjects have to be predicted, however. The variability in thermoregulatory response of individuals is quite large, as will be illustrated later in this thesis, and differences of a factor two in tolerance time for heat exposure between individual subjects are not uncommon (Havenith, 1987). This also presents a problem when safety limits have to be defined. These are often defined using the 95th or 99th percentile of the population as reference and not the average, to avoid any risk of heat illness. When actual work places are evaluated, it is shown that according to e.g. ISO 7933 many workplaces in the mining industry, where few problems are observed, are well above the standard's safety limits (Kampmann, 1992). Mentioned limits are for the 95th percentile of the population, but workers at these locations are fitter than average and also acclimatized. Thus, the limit values used are far too conservative for this group of acclimatized subjects. The dilemma here is the struggle between safety for all on one hand and the difficulty to adjust limits to the individual on the other.

These findings illustrate that further improvement in heat stress and strain prediction may be achieved when mechanisms of individual responses and relations between individual characteristics and heat stress response are clarified and introduced in the models. This will be the goal of this thesis.

1.2 Background

1.2.1 Individual characteristics and heat stress

Extensive reviews of factors which may influence the response of an individual to heat exposure were published by Havenith (1985, 1987) and Kenney (1985). Discussed factors were: aerobic power, acclimation state, morphological differences, circulation and hydration state, race, gender, age, circadian rhythms, and use of drugs. The main conclusions for the effects of these factors will be discussed below.

A more detailed discussion is presented in the chapters which deal with the experimental data.

Morphology and fat

Differences in body size and body composition between subjects affect thermoregulation through their effect on the physical process of heat exchange (insulation, surface/mass ratio) and through differences in the body weight subjects have to carry. Body surface area determines the heat exchange area for both dry and evaporative heat and thereby affects reactions to heat stress (McArdle et al., 1984). In comparisons between animal species, a high surface to mass ratio is in general considered beneficial for the capacity to tolerate heat stress (Bergman, 1847, Allen 1906, Austin and Lansing 1986).

Body mass determines metabolic load when a subject is involved in a weight-bearing task like walking. This implies that mass correlates positively with heat production. Body mass also determines body heat storage capacity. This is relevant with passive heat exposures, or when heat loss is limited and body temperature increase is determined by storage capacity.

The effect of body fat content is somewhat confounded with that of body mass: Body fat presents a passive body mass, which affects metabolic load during weight -bearing tasks.

In the cold, subcutaneous fat determines the physical insulation of the body (conductivity of muscle=0.39, fat=0.20 $W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$,). However, as the fat layer is well perfused by blood flowing to the skin in warm conditions, it is not expected to hamper heat loss during heat exposure (Burse, 1979). The blood flow provides a convective shortcut for heat transport from core to skin. When blood flow increases from resting to "hot" levels, the heat flow passing through the fat layer by conduction is reduced from over 80% to less then 5% of total heat flow due to the increase in convective heat flow (Stolwijk, 1971). Further, as the specific heat of body fat is about half that of fat free body tissue, people with equal mass but higher fat content will heat up faster at a certain storage rate (Bar-Or et al., 1969).

As the number of sweat glands remains constant with ageing, increasing body fat content, with the concomitant increase in body size, will result in a reduced sweat gland density (Bar-Or et al., 1969). With extreme obesity, cardiac function is reduced, which also leads to reduced heat tolerance (Bar-Or et al., 1969).

Aerobic power

Within the prescriptive zone[3] (Leithead and Lind, 1964, Lind et al., 1970) body core temperature during work is related to oxygen uptake (metabolic rate), relative to the

[3]The prescriptive zone was defined as the climate range in which a person can reach thermal equilibrium. Above this range, a steep rise in body temperature is observed. The location of the zone in the climatic spectrum is dependent on metabolic heat production and clothing insulation.

individuals' maximal aerobic power (%$\dot{V}O_{2\,max}$; Saltin and Hermansen, 1966; Åstrand, 1969; Nielsen, 1969). On the warm side, outside the prescriptive zone, also a strong effect of aerobic power on heat stress response is expected. The $\dot{V}O_{2\,max}$ of a subject is thus inversely related to the heat strain of a subject in the heat, mainly through its beneficial effect on circulatory performance. The higher the aerobic power, the higher the circulatory reserve (the capacity for additional increase in cardiac output) when performing a certain task. Further, aerobic power is often confounded with acclimatization as training can result in an improvement of the acclimatization state. This is caused by the increase in body temperature which normally occurs with exercise. The result is a reduction of heat strain in warm climates (Henane et al., 1977; Avellini et al., 1982). This effect works both through circulation and through improved sweat response.

Acclimatization state

A subject's state of acclimatization appears to be of great influence on his reaction to heat stress (Fox, 1968; Senay et al., 1976). With increasing acclimatization state, the heat strain of the body will be strongly reduced, resulting in lower core temperature and heart rate during a given exercise in the heat. This is related to improved sweat characteristics (setpoint lower and gain higher, better distribution of sweating over the body and higher efficiency of sweating (higher evaporated/produced ratio (Fox et al., 1963; Collins et al., 1966; Nadel et al., 1974)) and improved circulatory stability (better fluid distribution, faster fluid recruitment from extracellular space, reduced blood pressure decrease) during exercise in the heat (Senay and Kok, 1977). The individual state of acclimatization can be changed by regular heat exposure, e.g. due to seasonal changes in the natural climate or by heat acclimation due to regular artificial (e.g. climatic chamber) heat exposure. Subjects living in the same climatic conditions can differ in acclimatization status, however, mainly due to the above mentioned difference in regular training activity. The combination of heat and exercise induces most optimal acclimatization (Fox et al., 1963). Not all subjects acclimatize equally well: some subjects do not show acclimatization effects at all when exposed to heat regularly (Wyndham et al., 1967, Strydom, 1980)

Circulation and hydration state

Havenith (1985, 1987), putting together results from several sources (Nielsen, 1973, 1974a,b; Claremont et al., 1976; Nadel et al., 1980; Gaebelein and Senay, 1980; Fortney et al., 1981), concluded that changes in plasma volume and changes in plasma osmolality independently influence the change in core temperature during heat stress.

Lowering plasma volume due to hypohydration, is associated with changes in blood viscosity (increase), venous return and stroke volume (both lower) (Nadel, 1980). Cardiac efficiency (in terms of energy cost per volume output) during hypohydration will therefore be reduced, but it hardly changes in hyperhydration (Nadel, 1980). During work and/or heat exposure, the need for blood supply to muscles and skin is increased (for work and for heat loss respectively). Supplying this blood, the cardiac filling pressure decreases more drastically in hypohydration, which is compensated for by vasoconstriction of the blood vessels in the skin, reducing the skin blood flow. This decreases the heat conductance of the skin, which results (in that same environment, at equal sweat rates) in lower skin temperature and increased core temperature (Nadel, 1980).

Nielsen (1974[b]) suggests that the effect of plasma osmolality may be ion specific and acts either on the thermoregulatory centres in the brain, or directly on the function of the sweat gland.

By means of these mechanisms, hypohydration has a deteriorating effect on thermal control. Hyperhydration works the opposite (beneficial) way, be it to a lesser extent.

Gender

Investigating effects of subject's gender on heat stress response, investigators (Hardy and DuBois 1940; Wyndham et al., 1965; Morimoto et al., 1967; Fox et al., 1969; Cunningham et al., 1978) found that females had higher core temperatures, skin temperature, heart rates, blood pressure, and setpoints for sweating, in comparison to males. Thus on a population level, women may seem to be less tolerant to heat then men. However, on a population level females differ also in many physical characteristics from men, which may confound the gender issue in thermoregulation. A more precise evaluation of the gender effect was described by authors, who compared gender groups which were matched in as many other characteristics ($\dot{V}O_{2\,max}$, %fat, size) as possible (Davies, 1979; Avellini and Kamon, 1980; Shapiro et al., 1980; Frye and Kamon, 1981). They observed that gender differences in thermoregulation are minimal, and that some of these differences are climate specific (females perform better in warm, humid; worse in hot dry climates).

Two specific female processes do effect thermoregulation: the menstrual cycle and menopause. The effect of the menstrual cycle at rest (a higher core temperature (T_{co}) in the post ovulatory phase) was almost absent during exercise and or heat exposure, however. Avellini and Kamon (1980), Frye et al., (1982), and Horvath and Drinkwater (1982), found that existing male-female differences during exercise heat stress disappeared with acclimation, or that they were completely absent from the beginning.

Also the effect of menopause on thermoregulation during heat exposure has been studied. Post menopausal hot flashes and night sweating provide anecdotal evidence that thermoregulation is affected by oestrogen withdrawal. It has been suggested that during these episodes, setpoint body temperature is lowered, resulting in heat loss effector reactions (Kronenberg and Barnard, 1992). Kenney and Anderson (1988) observed at equal stress levels higher core temperatures in postmenopausal women compared to young females with equal aerobic power levels. Acute oestrogen replacement therapy reduces cardiovascular and thermoregulatory strain in postmenopausal women (Tankersley et al., 1992).

Age

Research on the effect of age on heat stress response has followed similar methods as research on gender differences. On a population basis, reduced heat tolerance of older subjects was observed (Hellon et al., 1956 Hellon and Lind, 1958; Lind et al., 1970; Wagner et al., 1972). However, the age groups differed in more parameters than just age. Older subjects were less fit, had more body fat, etc. When investigators started to correct for these differences, it was found that differences in heat strain between age groups disappeared (Kenney and Anderson, 1988, Kenney and Havenith, 1993) or that older subjects even showed better performance (Pandolf et al., 1988). Though heat strain may be similar, some differences in effector function remained present between age groups: older subjects had reduced skin perfusion and lower sweat capacities (Anderson and Kenney, 1987). Matching of age groups for all other personal characteristics was never perfect however, which prevents drawing a final conclusion on the age effect.

Circadian rhythm

Although not really an individual characteristic, circadian rhythm may be important to the topic. Confounding of time of day with subject's individual thermoregulatory reaction in a test can influence the results since body temperature fluctuates with a circadian rhythm (Gierse, 1842; Davy, 1845). Aschoff and Heise (1972) showed that changing skin blood flow is the main effector mechanism in this circadian process. Whether this results in changing performance or tolerance during the circadian cycle is yet unclear.

Hypertension

Studies of the role of hypertension in heat tolerance showed reduced circulatory performance in hypertensives compared to normotensives (Kenney et al., 1984). Though no differences between groups were present in heart rate and core temperature response, reduced forearm blood flows were observed in hypertensives as well as reduced stroke volumes and cardiac output. This indicates a reduced heat transport capacity from body core to the skin and thus an increased risk of overheating. Sweat rate was higher in the hypertensives, however, which may have compensated for the circulatory differences. It is difficult to estimate whether this compensation will also be effective in other climatic or work conditions. A certain increased risk seems present.

Drugs

Use of drugs such as alcohol may predispose subjects to heat illness by changes in physiological effector mechanisms and by changes in behaviour. Reviews by Minard (1980) and Chick et al., (1988) list drugs which are potentially harmful in heat exposure. The relevant drugs have mainly effects on the body fluid balance, vasoconstrictor/dilator activity and on cardiac function. These include: alcohol, diuretics, anti-cholinergic drugs, vasodilators, anti-histamines, muscle relaxants, atropine, tranquillizers and sedatives, β-blockers and amphetamines. Especially anti-hypertensive drugs deserve attention because of their widespread use.

1.2.2 Climatic factors

The climate directly affects the capacity of a subject to exchange heat with the environment. Air and radiative temperature affect dry (convective and radiative) heat loss and the ambient vapour pressure determines the heat loss capacity for that climate with respect to evaporative heat loss. Wind affects both dry and evaporative heat loss coefficients for nude subjects in a similar fashion (Havenith et al., 1990a,b).

Climatic parameters (temperature, humidity, wind) also show an interaction with individual characteristics, however. To describe these relations and interactions in heat exposures, two research paradigms are mostly used: exposure to warm, humid heat and to hot, dry heat. Many researchers have selected such climates in a way that both climates should be equally stressful (according to e.g. the WBGT index), but that the main avenues for heat loss in both climates are different. In a warm humid climate, evaporative heat loss is limited, and thus the body has to lose its surplus heat by convection and radiation. In the hot dry climate on the other hand, convective and radiative heat transport will be directed towards the body, and thus the subject will depend on his evaporative heat loss capacity to maintain thermal equilibrium. Dry heat loss capacity is directly related to the surface area of a subject, as well as to the subject's capacity to increase skin temperature by increasing blood flow. Evaporative heat loss is dependent on heat loss surface area too, but also on sweating capacity (total quantity and distribution over the body) and thus through this on acclimatization state and fitness. Also, increasing skin temperature can result in increased evaporation, thus the skin blood flow capacity also plays a role.

1.2.3 Work

Two important relations between work and heat stress can be distinguished: mechanical work efficiency and work type in terms of weight-bearing versus non-weight-bearing tasks. The task a subject has to perform determines both his metabolic rate and his metabolic heat production rate (= metabolic rate - external work rate). Metabolic rate and heat production rate are almost equal when the task performed has minimal or zero mechanical efficiency. This is the case e.g. in level walking. In other activities, like walking up a grade, mechanical efficiency increases due to delivered potential energy. Maximal values range around 21% (gross efficiency; Hesser et al., 1977) i.e. for cycling. In the latter case metabolic heat production thus amounts to 79% of metabolic rate. Another extreme is negative work (e.g. downhill walking), where the internal heat production rate is higher than metabolic rate, thus presenting a negative efficiency (Kamon, 1970). When comparing reactions of subjects to different tasks, these differences in heat liberation in the body should be taken into consideration.

A second factor in the effect of a task on thermoregulatory performance is the difference between weight-bearing tasks and non-weight-bearing tasks, as this difference interacts with individual characteristics. In non-weight-bearing tasks, like (ergometer) cycling, metabolic rate is determined purely by external factors as wind and (ergometer) resistance. In weight-bearing tasks like in level walking or walking on a grade, metabolic rate, and thus also the amount of heat liberated in the body, is directly related to body mass. In the latter case, metabolic rate is fairly equal between subjects when expressed per kg of body weight (Pandolf et al., 1977). When people have to carry loads additional to their body weight, not only total mass (body + load) is important, but also the ratio between the carried and the total mass (Epstein et al., 1987) and the way the load is carried (Holewijn, 1986, 1990).

1.2.4 Clothing

Clothing affects heat loss from the body to the environment. It forms a resistance to both dry heat exchange with the environment and to evaporative heat exchange. Though evaporative heat resistance differences between garments usually parallel the dry heat resistance differences, vapour resistance can also be very high at low heat resistances due to layers in the clothing with reduced vapour permeability (e.g. rain wear). Clothing can change the climate to which the skin is exposed. Microclimate air (between skin and clothing) in warm environments will have a temperature and a vapour pressure intermediate of that at the skin and in ambient air. This microclimate, similar to the ambient climate can interact with the influences of inter-individual differences. E.g. in a suit which is impermeable to water vapour, a high sweat capacity (related to a high level of acclimatization), which usually is an advantage in the heat, now changes into a disadvantage. Most sweat will just drip off or be absorbed in the underclothing and hardly contribute to heat loss. A high sweat loss will result in faster dehydration. This may thereby put an acclimatized person at a disadvantage (Havenith, 1987).

The human body's thermal sensors do not distinguish between a certain microclimate and a similar ambient climate. Therefore, when the microclimate characteristics are known, it is possible to study the importance of clothing for the individual's heat loss without actually incorporating clothing into the experiments by using the predicted microclimate specifications as ambient climate. These predictions can be made using models in which clothing heat transfer characteristics are incorporated (Lotens, 1993).

1.3 Methodology

1.3.1 Experimental section

Subject selection

Studies of inter-individual differences and their effect on thermoregulation have so far been aiming at the study of one parameter at the time, keeping all others equal. Ideally, groups are compared which were matched for all but the one parameter under study. Although methodologically sound, attempts to evaluate the role of individual characteristics in a matched groups research paradigm has not always yielded conclusive answers to questions of the effect of certain parameters for several reasons. In most studies in which various features of subject groups have been matched, authors did not succeed in matching all potentially important characteristics. For example when studying age differences, matching older and younger subjects on the basis of $\dot{V}o_{2\,max}$ per kg body mass, often differences in absolute $\dot{V}o_{2\,max}$ of 10-15% between groups remained present in the data (Anderson and Kenney, 1987; Kenney and Anderson, 1988). Also groups matched for $\dot{V}o_{2\,max}$, often differ in habitual exercise levels. This often makes interpretation of results less clear. Furthermore, these designs are unable to ascertain the *relative* importance of individual characteristics for heat stress response in relation to each other. Questions which need answering are of the type: "if a person is overweight, but also well trained, do these characteristics compensate for each other in determining heat stress response?" This type of questions is difficult to answer based on results from studies of a single characteristic.

For these reasons, in the present study a different method was used to gather data for the present study. Specifically, an attempt was made to determine the relative importance of individual characteristics. For this purpose, in different experimental settings with respect to climate and work type, a subject sample was recruited which was heterogeneous for relevant individual characteristics and in which individual characteristics were minimally inter-correlated. These subjects were then exposed to a combined work-climate stress and their reactions, in terms of physiological variables (core temperature, heart rate, sweat rate etc.), were subsequently analysed for the contribution of individual characteristics using the technique of multiple regression. From the factors mentioned in section 1.2 six were selected to be studied (Havenith, 1985): $\dot{V}o_{2\,max}$, physical activity level, anthropometry, adiposity, gender and age (as including age required a strong increase in subject numbers to maintain

statistical power, this parameter was only added in one of the studies). Others were excluded as described later.
Apart from the relative importance of individual characteristics, also the interactions between these characteristics and the climate type and the work intensity were studied.

Excluding certain effects
Not all possible effects mentioned in section 1.2 are dealt with in this study. Several effects which are important but are not in essence individual characteristics, such as acclimatization, circadian rhythm, hydration state, hypertension and drug use, are excluded. This has been achieved by performing experiments after a cool period (winter, spring) only, to avoid acclimatization effects, within a certain time of day range only, by using hydrated subjects and assuring equal rehydration, by excluding subjects with a history of hypertension and finally by excluding all users of drugs (users of coffee, tobacco and alcohol were requested to minimize use the day before the experiment and to refrain from use the last 2 hours before the test).

Climate
As mentioned above, the impact of certain individual characteristics on heat stress response is expected to interact with climate type. Two climates were selected for the experiments, which on a group level should result in equal strain (equal WBGT), but which may interact differently with different individual characteristics. Thus, subjects were exposed to either a warm humid climate (35°C, 80% relative humidity (r.h.)) or a hot dry climate (45°C, 20% r.h.). In one series of experiments an additional exposure to a cool climate (21°C, 50% r.h.) was added as an exercise without heat reference. Variations in wind or additional radiation were not added to the climate parameters, as this would increase the number of conditions drastically.

Work
Using a fixed, equal work load for all subjects allows the evaluation of the relative importance of all individual parameters at once. However, as mentioned in section 1.2.1, the general idea found in the literature is that heat stress response over a wide range of climatic conditions is mainly determined by work load expressed as a percentage of the individual's maximal load (%$\dot{V}O_{2\,max}$). Therefore, in many studies the subjects perform work relative to their individual maximum. Doing so, the effect of differences in aerobic power between subjects on the heat stress response will be minimized. This is useful when the issue is not comparing the effect of aerobic power with that of other parameters, but instead more subtle effects (not aerobic power) are the subject of study. Then, a correction for aerobic power differences is desired. For this reason, in the present study both fixed and relative work loads (%$\dot{V}O_{2\,max}$) will be used.

Another reason for using both fixed as well as relative work intensities is the relation with actual work situations. Work might have a fixed pace due to the work organization, which compares best to the fixed load. Alternatively, the work may be individually organized, which may represent conditions of an equal load for all or of a load relative to the individual's maximum, depending on work organization and personal motivation.

The exercise mode chosen for the experiments was bicycle ergometer work, as measurement of forearm blood flow in walking subjects is virtually impossible. Also, with this mode no weight correction for the setting of work load is necessary.

As actual work load, in the fixed condition a load of 60 W was chosen. This choice was based on the need to let even the least fit subject finish a 1 hour work bout at this level. Also this work level relates to the level people are able to work on for an 8 hour work shift ($\dot{V}O_2$ approx. 1 l·min^{-1}). The choice of relative load was made for 30 min. at 25 %$\dot{V}O_{2\,max}$, followed by 30 min. at 45%$\dot{V}O_{2\,max}$. This work rate again aiming at allowing the least fit subject to finish the test.

Table 1 Matrix of measuring conditions, with respect to climate and work type. Performed experiments are marked with a "★".

climate type:	work type: Bicycle Ergometry absolute load (60 Watt)	 relative load (25 and 45%$\dot{V}O_{2\,max}$)
warm humid (35°C, 80%r.h., WBGT=31.9)	★	★
hot dry (45°C, 20%r.h., WBGT=31.4)	★	★
cool (21°C, 50%r.h., WBGT=16.7)	—	★

climate x work

Combining the considerations with respect to the work type with those relating to the choice of climates as discussed in the previous section, the result is the matrix of main measuring conditions presented in Table 1. The cool condition was only performed for the relative work load condition. For the cool environment, data from literature show that $\dot{V}O_{2\,max}$ is an extremely strong determinant of the individual's body temperature increase (see par. 1.2.1). An experiment with a fixed work load in that climate was expected to need very large numbers of subjects to show effects of other individual parameters. It was therefore regarded more efficient to study the reaction to a cool environment with a work load standardized for the individual's $\dot{V}O_{2\,max}$: a relative work load. This supposedly increased the test's sensitivity (i.e. needing a lower number of subjects) to characteristics other than $\dot{V}O_{2\,max}$.

1.3.2 Statistics

Statistical analysis is an important issue in this study. As the problems are investigated in an epidemiological way (many parameters vary at the same time), the approach of multiple regression was chosen. Strain indicators, as e.g. rectal temperature, were taken as dependent variable in the analysis and individual characteristics as independent parameters. First the type of distribution of the data is investigated (normal or logarithmic, skewness and kurtosis), and the inter-correlation of "independent" parameters tested. Next the regression analysis is performed stepwise in an interactive manner. This means that the correlation of all independent parameters with the dependent variable is determined, after which the "best" parameter is selected. This was done both on the basis of the highest Pearson correlation coefficients, as well as on the basis of physiological relevance of the parameter (as decided by the author). This last criterion was mainly applied when several independent parameters show partial correlations with the dependent variable which are very close together. Next this parameter is entered into the equation, the data set corrected for the effect of this parameter, and the residual variance in the dependent variable calculated. After this the cycle is started again with the partial correlations of the remaining independent parameters with the residual variance in the dependent variable. The cycle is repeated until no significant (partial) correlations are found. For this approach the statistical program SYSTAT (Wilkinson, 1990) was used, as this has the option of interactive multiple regression.
This basically leads to one regression equation. However, in some cases more than one combination of independent parameters is possible, with similar explanatory power. These alternatives were explored and, when of interest, will be presented.

Linearity of effects was studied using plots of responses or residuals versus parameters. In some cases non-linear relations could be tested. When of interest, these will be reported.
The additivity of effects was studied for a limited number of parameters. These individual parameters were re-coded into discrete levels (e.g. low, middle and high $\dot{V}O_{2\,max}$), after which their effect and interaction with other parameters was studied using analyses of variance. Due to the limited number of subjects (and thus degrees of freedom), only few combinations could be analysed which did not reveal relevant interactions. Therefore the analyses concentrated on main effects.

In the presentation of the results, both the regression coefficients and standardized regression coefficients will be given. As the relative contribution of individual characteristics is of interest, these standardized coefficients are more informative. They correct the regression coefficients for the effects of the unit used (e.g. using grams instead of kg, leads to a difference in regression coefficient of a factor 1000, based on the same data, but will show an unchanged standardized regression coefficient) and for the range of the values of parameters (0.5°C change in T_{co} is much more stressful than the same change in skin temperature).

In chapter 5, differences between correlation coefficients were compared, using the relevant module in STATISTICA (1995).

The relative contributions of the parameters will be illustrated by pie-charts. As no reference for this approach is known to us yet, this will be explained in more detail here.

In these pie-charts the total amount of explained (adjusted r^2 value) and unexplained variance will be shown. The segment of explained variance will be divided over the contributing parameters. This division was not made according to the added variance per step (=added parameter) in the stepwise regression as is often seen in literature. This approach does not give information on the relative importance of the parameters. Instead the standardized regression coefficients will be used to divide the explained variance according to the relative contributions of the parameters. For this the following equation was used:

$$\textit{contribution to } r^2 = \frac{|\textit{standardized regression coefficient for parameter}|}{\sum |\textit{all standardized regression coefficients in equation}|} \cdot r^2$$

The absolute values are taken, as the standardized regression coefficient can be both positive and negative.

Keeping in mind that a standardized regression coefficient of 1 implies that a change of one standard deviation (SD) in the independent parameter would result in a change of 1 SD in the dependent variable, the denominator of the equation presented above, represents the maximal change (in SD units) of the dependent variable when all independent parameters change by one SD. Due to the effect of the sign of the coefficient, this change in the dependent parameter has to be in the direction which gives for all independent parameters the same direction of change in the dependent variable. To give an example, let's assume that heart rate (HR) is explained by age (standardized regression coefficient = +0.35) and by $\dot{V}O_{2\,max}$ (stand. regr. coeff. = -0.50). The explained variance in the pie chart would therefore be for age:

$$\textit{age segment} = \frac{|+0.35|}{|+0.35| + |-0.50|} = 0.41 \textit{ of } r^2$$

and for $\dot{V}o_{2\,max}$:

$$Vo_{2max}\ segment = \frac{|\ -0.50\ |}{|\ +0.35\ |\ +\ |\ -0.50\ |} = 0.59\ of\ r^2$$

The value of the denominator here implies that if we go from a low age, high $\dot{V}o_{2\,max}$ person to a high age, low $\dot{V}o_{2\,max}$ person with a one SD change in both parameters (up for age, down for $\dot{V}o_{2\,max}$), that the difference in heart rate would amount to 0.85 SD. As the following chapters will show, this method works well in practice. It should not be used, however, when an inter-correlation between independent parameters is present. In the presented studies, this was monitored by looking at the tolerance levels of parameters in the equation.

1.3.3 Modelling

It is anticipated that the interpretation of many parameters at a time may be a difficult job. A structured way to show the results of the analysis in a quantitative way is to develop a computer model which includes the observed mechanisms. This will produce the experimentally observed reactions, if correct, and allows for exercises that improve insight. For this purpose an existing model of thermoregulation and heat exchanges (Gagge et al., 1986; Lotens, 1993) was taken as a starting point. Using data from literature, this model (programmed in FORTRAN) was adapted to represent the individual characteristics. Next, the goodness of fit of the model was tested using the data collected for this thesis. Thus the new data sets were not used for model development, but only for its validation.
Several models could have been chosen as a starting point, with different levels of complexity and published validity. However, as the main aim of this thesis is to show that incorporation of individual characteristics in a model will improve predictive power, the choice of the model itself is not essential. The results of this study are relevant to all thermoregulatory models which do not yet incorporate individualization. Therefore, the choice for a readily available, physiologically simple model was made. That this model also incorporates extensive clothing physics increases its potential for future use.

1.4 Outline of this study

Combining the considerations on the work type with those relating to the choice of climates as discussed in the previous section, the result is the matrix of main measuring conditions presented in Table 1. In Table 2, the matrix also shows the chapters in which the experiments relating to those conditions are described.

Chapter 2 describes an experiment in which male and female (n=56) subjects are exposed to a warm humid climate while performing work on a cycle ergometer at a fixed load of 60 watts. The resulting heat strain is discussed in terms of the influence of individual characteristics, with emphasis on the effects of $\dot{V}O_{2\,max}$, body size, adiposity and age. The ages of the subjects were equally distributed between 20 and 73 years. Besides linear effects of age, non-linear effects are studied.
As the addition of age to the experimental design necessitates a very large subject group, this parameter was not studied in the other conditions. The warm humid climate was chosen for inclusion of age, as this was supposedly the most relevant climate in relation to age related heat stress problems.

In chapter 3, an identical test to the one in chapter 2 is discussed, which is performed with young subjects of both genders only however (n=27). For this purpose the young group of chapter 2 was extended. Exclusion of the age factor is expected to give a more sensitive analyses of the other individual parameters involved.

Table 2 Matrix of measuring conditions, with respect to climate and work type and the number of the chapter(s) in which they are discussed.

climate type:	work type: Bicycle Ergometry	
	absolute load (60 Watt)	relative load (25 and 45%$\dot{V}O_{2\,max}$)
warm humid (35°C, 80%r.h.)	2, 3, 5	4, 5
hot dry (45°C, 20%r.h.)	5	4, 5
cool (21°C, 50%r.h.)	—	4, 5

In chapter 4 an experiment with a young, mixed gender, subject group (n=24) which was exposed to three climates: hot dry, warm humid, and cool is discussed. In this case subjects were asked to work at intensities relative to their maximal aerobic power. Data for all conditions were first lumped in one analysis providing information on the relevance of individual differences for exposure to a mix of climates. As the differences in climate might have an effect interacting with the inter-individual differences, the data were also analysed for the presence of this interaction.

Chapter 5, discusses a similar experiment to the one of chapter 3, with a different young, mixed gender, subject group (n=30) exposed to a hot dry climate.
This chapter also presents an integrated discussion of these data with those of chapters 3 and 4, and focuses on the interactions between individual characteristics,

climate type and work intensity in the determination of heat strain. This chapter concludes the experimental section.

Chapter 6 presents the work on the integration of individual characteristics in a computer model of human temperature regulation and heat exchanges with the environment. Further, the effect of the additions to the model will be evaluated using the data sets of chapters 2 to 5 for validation purposes, comparing the new model with the original model's performance and with the performance of the regression models of chapter 5.

Chapter 7 shows example simulations to demonstrate the effects of the introduction of individual factors in the model.

Finally, a summary of the thesis is presented, as well as suggestions for future research.

REFERENCES

Adolph EF (1947) *Physiology of man in the desert.* Interscience; New York

Allen JA (1906) *The influence of physical conditions in the genesis of species.* Ann Rep Smithsonian Inst 375-402

Anderson RK and Kenney WL (1987) *Effect of age on heat-activated sweat gland density and flow during exercise in dry heat.* J Appl Physiol 63:1089-1094

Aschoff J, Heisse A (1972) *Thermal conductance in man: its dependence on time of day and on ambient temperature.* In S Itoh (ed): Advances in climate physiology Springer Verlag 334-347

Åstrand I (1969) *Aerobic work capacity in men and women with special reference to age.* Acta Physiologica Scandinavia 49(Suppl) 169:1-92

Austin DM, Lansing MW (1986) *Body size and heat tolerance: A computer simulation.* Human Biology 58:153-169

Avellini BA, Kamon E(1980) *Physiological responses of physically fit men and women to acclimation of humid heat.* J Appl Physiol 49:254-261

Avellini BA, Shapiro Y, Fortney SM, Wenger CB and Pandolf KB (1982) *Effects on heat tolerance of physical training in water and on land.* J Appl Physiol 53:1291-1298

Bar-Or O, Lundgren HM, Buskirk ER (1969) *Heat tolerance of exercising obese and lean women.* J Appl Physiol 26:403-409

Belding HS, Hatch TF (1955) *Index for evaluating heat stress in terms of physiological strain.* Heat piping and Air conditioning 27:129-136

Bergman C (1847) *Über die Verhältnisse der Wärmeökonomie der Tiere zu ihrer Grösse.* Göttinger Studien 1:595-708

Burse RL (1979) *Sex differences in human thermoregulatory response to heat and cold stress.* Human Factors 21:687-699

Chick TW, Halperin AK, Gacek EM (1988) *The effect of antihypertensive medications on exercise performance: a review.* Med Sci Sports Exerc 20:447-454

Claremont AD, Costill DL, Fink W, van Handel P (1976) *Heat tolerance following diuretic induced dehydration.* Medicine and Science in Sport and Exerc 8:239-24

Collins KJ, Crockford GW, Weiner, JS (1966) *The local training effect of secretory activity on the response of eccrine sweat glands* J Physiol (London) 184:203-214

Cunningham, DJ, Stolwijk JAJ, Wenger CB (1978) *Comparative thermoregulatory responses of resting men and women.* J Appl Physiol 45:908-915

Danielsson U (1993) *Convection coefficients in clothing air layers.* Thesis Stockholm Inst of Technology ISSN 1104-3008

Davies CTM (1979) *Thermoregulation during exercise in relation to sex and age.* Eur J Appl Physiol 42:71-79

Davy J (1845) *On the temperature of man.* Phil Trans 2:319-333

Epstein Y, Strochein LA, Pandolf KB (1987) *Predicting metabolic cost of running with and without backpack loads.* Eur J Appl Physiol 56:495-500

Fortney LE, Nadel ER, Wenger CB, Bove JR (1981) *Effects of blood volume on sweating rate and body fluid in exercising humans.* J Appl Physiol 51:1594-1600

Fox RH, Löfstedt BE, Woodward PM, Eriksson E, Werkstrom B (1969) *Comparison of thermoregulatory function in men and women.* J Appl Physiol 26:444-453

Fox RH (1968) *A review of studies on the physiology of heat stress.* Army Personnel Research Committee 68/A1

Fox RH, Goldsmith R, Kidd DJ, Lewis HE (1963) *Blood flow and other thermoregulatory changes with acclimatization to heat.* J Physiol (London) 166:548-562

Frye AJ, Kamon E, Webb M (1982) *Responses of menstrual women, amenorrheal women and men to exercise in a hot, dry environment.* Eur J Appl Physiol 48:279-288

Frye AJ, Kamon E (1981) *Responses to dry heat of men and women with similar aerobic capacities* J Appl Physiol 50:65-70

Gaebelein CJ, Senay LC (1980) *Influence of exercise type, hydration and heat on plasma volume shifts in men* J Appl Physiol 49:119-123

Gagge AP, Fobelets AP, Berglund LG (1986) *A standard predictive index of human response to the thermal environment.* ASHVE Transactions 92:709-731

Gagge AP, Stolwijk JAJ, Nishi Y (1971) *An effective temperature scale, based on a simple model of human physiological regulatory response.* ASHRAE Trans 74:247-262

Gagge AP (1983) *The science of clothing, a short history from a physiologist's viewpoint* Aspects medicaux et biophysiques des vetements de protection, Actes de la conference internationale, Lyon-Bron, 4-8 juillet, 13-21

Gierse A (1842) *Quaemiam sit ratio caloris organii.* Dissertation, Halle

Haldane JS (1905) *The influence of high temperatures.* J Hygiene 5:494-513

Hardy JD, Dubois EF (1940) *Differences between men and women in their responses to heat and cold.* Proc. NY Ac Sc 26:389-398

Havenith G, Heus R, Lotens WA (1990) *Clothing ventilation, vapour resistance and permeability index: changes due to posture, movement and wind.* Ergonomics 33: 989-1005

Havenith G, Heus R, Lotens WA (1990) *Resultant clothing insulation: a function of body movement, posture, wind, clothing fit and ensemble thickness.* Ergonomics 33: 67-84

Havenith G (1987) *Physiological parameters in heat tolerance* (in Dutch). Nederlands Militair Geneeskundig Tijdschrift 40:231-233

Havenith G (1985) *Individual parameters in thermoregulatory control; a review.* Report Institute for Perception, Soesterberg IZF1985-26.

Hellon RF, Lind AR, Weiner JS (1956) *The physiological reactions of men of two age groups to a hot environment.* J Physiol London 133:118-131

Hellon RF, Lind AR (1958) *The influence of age on peripheral vasodilation in a hot environment.* J Physiol London 141-262

Henane R, Flandrois R, Charbonnier JP (1977) *Increase in sweating sensitivity by endurance conditioning in man.* J Appl Physiol 43:822-828

Hesser CM, Linnarsson D, Bjurstedt H (1977) *Cardiorespiratory and metabolic responses to positive, negative and minimum load dynamic exercise.* Respiration Physiology 30:51-67

Holewijn M (1986) *Load carriage; a review* (in Dutch). Report Institute for Perception, Soesterberg IZF1986-28

Holewijn M (1990) *Physiological strain due to load carriage.* Eur J Appl Physiol 61: 237-245

Horvath SM, Drinkwater BL (1982) *Thermoregulation and the menstrual cycle.* Aviat Space Environ Med 53:790-794

Houghton FC, Yagloglou CP (1923) *Determining equal comfort lines.* Journal of ASHVE 29:165-176

ISO 7933 (1989) *Hot Environments-Analytical determination and interpretation of thermal stress using calculation of required sweat rate.* Geneva, International Standardization Organization

Kamon, E (1970) *Negative and positive work in climbing a laddermill.* J. Appl. Physiol., 1970, 29(1), 1-5

Kampmann B, Morfeld P, Piekarski C (1992) *Bewertung der ISO 7933: Vergleich der Beanspruchungsprognose der Norm mit Beanspruchungsmessungen bei Felduntersuchungen im Steinkohlenbergbau.* Zeitschrift fur Arbeitswissenschaft, 46 (18 NF) 1992/3

Kenney WL (1985) *Physiological correlates of heat intolerance.* Sports medicine, 2: 279-286

Kenney WL, Anderson RK (1988) *Responses of older and younger women to exercise in dry and humid heat without fluid replacement.* Medicine and Science in Sports and Exercise 20:155-160

Kenney WL, Havenith G (1993) *Heat stress and age - skin blood flow and body temperature.* Journal of Thermal Biology 18:341-344

Kenney WL, Kamon E, Buskirk ER (1984) *Effect of mild essential hypertension on control of forearm blood flow during exercise in the heat.* J Appl Physiol 56: 930-935

Kronenberg F, Barnard RM. (1992) *Modulation of menopausal hot flashes by ambient temperature.* J Therm Biol 17:43-49

Leithead CS Lind AR (1964) *Heat stress and heat disorders,* Cassel Publ. London

Lind AR, Humphreys PW, Collins KJ, Foster K, Sweetland KF (1970) *Influence of age and daily duration of exposure on responses of men to work in heat.* J Appl Physiol 28:50-56

Lotens WA (1993) *Heat transfer from humans wearing clothing.* Ph.D. Thesis, Delft University of Technology, February 1993, Delft

Lotens WA, Havenith G (1991) *Calculation of clothing insulation and vapour resistance.* Ergonomics 34:233-254

McArdle WD, Magel JR, Gergley TG, Spina RJ and Toner MM (1984). *Thermal adjustment to cold water in resting men and women.* J Appl Physiol 56:1565-1571

Minard D (1980) *Pre-employment and periodic medical examinations for workers on hot jobs.* Proceedings of a NIOSH workshop on recommended heat stress standards, US dept of health and human services, NIOSH, Cincinnati

Morimoto T, Slabochova Z, Naman RK, Sargent F II (1967). *Sex differences in physiological responses to thermal stress,* J Appl Physiol 22:526-532

Nadel ER, Pandolf KB, Roberts MF, Stolwijk JAJ (1974) *Mechanism of thermal acclimation to exercise and heat.* J Appl Physiol 37:515-520

Nadel ER (1980) *Circulatory and thermal regulations during exercise.* Federation Proc. 39:1491-1497

Nadel ER, Fortney SM, Wenger CB (1980) *Effects of hydration state on circulatory and thermal regulations.* J Appl Physiol 49:715-721

Nielsen R, Olesen B, Fanger PO (1985) *Effect of physical activity and air velocity on the thermal insulation of clothing.* Ergonomics 28:1617-1632

Nielsen B (1974a) *Effects of changes in plasma volume and osmolarity on thermoregulation during exercise.* Acta Physiol Scand 90:725-730

Nielsen B (1969) *Thermoregulation in rest and exercise.* Acta Physiologica Scandinavica, Suppl 323:7-75

Nielsen B (1973) *Metabolic reactions to cold during swimming at different speeds.* Arch Sci Physiol 27:A207-A211

Nielsen B (1974b). *Effect of changes in plasma Na^+ and Ca^{++} ion concentration on body temperature during exercise.* Acta Physiol Scand. 91:123-129

Olesen BW, Sliwinska E, Madsen TL (1982) *Effect of body posture and activity on the thermal insulation of clothing: measurements by a movable thermal manikin.* ASHRAE transact 82:791-805

Pandolf KB, Cadarette BS, Sawka MN, Young AJ, Francesconi RP, Gonzalez RR (1988) *Thermoregulatory responses of middle-aged and young men during dry-heat acclimation.* J Appl Physiol 65:65-71

Pandolf KB, Givoni B, Goldman RF (1977) *Predicting energy expenditure with loads while standing or walking very slowly.* J Appl Physiol REEP 43:577-581

Saltin B, L Hermansen (1966) *Oesophageal, rectal and muscle temperature during exercise.* J Appl Physiol 21:1757-1762

Schickele E, (1947) *Environment and fatal heat stroke.* The Military Surgeon, 100: 235-256

Senay Jr LC, Mitchell D, Wyndham CH (1976) *Acclimatization in a hot, humid environment: Body fluid adjustments.* J Appl Physiol 40:786-796

Senay LC, Kok R (1977) *Effects of training and heat acclimatization on blood plasma contents of exercising men.* J Appl Physiol, 43:591-599

Shapiro Y, Pandolf KB, Avellini BA, Pimental NA, Goldman RF (1980) *Physiological responses of men and women to humid and dry heat.* J Appl Physiol 49:1-8

Statistica (1995) Statsoft Inc Tulsa OK 74104

Stolwijk JAJ (1971) *A mathematical model of physiological temperature regulation in man.* Report of NASA contractor no CR 1855

Strydom NB (1980) *Heat intolerance: Its detection and elimination in the mining industry.* South African Journal of Science 76:154-156

Tankersley CG, Nicholas WC, Deaver DR, Mikita D, Kenney WL (1992) *Estrogen replacement in middle-aged women: thermoregulatory responses to exercise in the heat.* J Appl Physiol 73:1238-1245

Wagner JA, Robinson S, Tzannkoff SP, Marino RP (1972) *Heat tolerance and acclimatization to work in the heat in relation to age.* J Appl Physiol 33:616-622

Werner J (1989) *Thermoregulatory models. Recent research, current applications and future development.* Scand J Work Environ Health 15 Suppl 1:34-46

Werner J, Webb P (1993) *A six-cylinder model of human thermoregulation for general use on personal computers.* The annals of physiological anthropology 12:123-134

Wilkinson L (1990) *SYSTAT: the system for statistics.* Systat, Evanston, Il

Wissler EH (1982) *An evaluation of human thermal models.* Report on a workshop, University of Austin, Texas 13-15

Wissler EH (1964) *A mathematical model of the human thermal system.* Bulletin of mathematical biophysics, 26:147-167

Wyndham, CH, Strydom NB, Williams CG, Heyns, A (1967) *An examination of certain individual factors affecting the heat tolerance of mine workers.* J of the South African Institute of Mining and Metallurgy 68:79-91

Wyndham CH, Morrison JF, Williams CG,(1965) *Heat reactions of male and female Caucasians.* J Appl Physiol 20:357-364

Yaglou CP, Minard D, (1957) *Control of heat casualties at military training centers.* Archives of Industrial Health 16:302-31

2

Age predicts cardiovascular, but not thermoregulatory, responses to humid heat stress

Chapter 2

Age predicts cardiovascular, but not thermoregulatory, responses to humid heat stress

George Havenith · Yoshimitsu Inoue · Viktor Luttikholt · W. Larry Kenney

(European Journal of Applied Physiology, 70:88-96, 1995)

Summary Cross-section comparisons of the effect of age on physiological responses to heat stress have yielded conflicting results, in part because of the inability to separate chronological age from factors which change in concert with the biological aging process. The present study was designed to examine the relative influence of age on cardiovascular and thermoregulatory responses to low intensity cycle exercise (60 W for 1 h) in a warm humid environment (35°C, 80% relative humidity). Specifically, the relative importance of age compared to other individual characteristics [maximal oxygen uptake ($\dot{V}O_{2\,max}$), physical activity level, anthropometry, and adiposity] was determined by multiple regression analysis in a heterogeneous sample of 56 subjects in which age (20-73 years) and $\dot{V}O_{2\,max}$ (1.86-4.44 $l \cdot min^{-1}$) were not interrelated. Dependent variables (with ranges) included final values of thermoregulatory responses [rectal temperature (T_{re}, 37.8 - 39.2°C), calculated heat storage (S, 3.4-8.1 $J \cdot g^{-1}$), sweat loss (238-847 $g \cdot m^{-2}$)] and cardiovascular responses [heart rate (HR, 94-176 $beats \cdot min^{-1}$), forearm blood flow (FBF, 5.3-31.3 $ml \cdot 100ml^{-1} \cdot min^{-1}$), mean arterial blood pressure (MAP, 68-122 mmHg), and forearm vascular conductance (FVC = $FBF \cdot MAP^{-1}$, 0.06-0.44 $ml \cdot 100ml^{-1} \cdot min^{-1} \cdot mmHg^{-1}$). Age had no significant influence on T_{re}, S, or sweat loss, all of which were closely related to $\dot{V}O_{2\,max}$. On the other hand, HR, MAP, FBF, and FVC were related to both age and $\dot{V}O_{2\,max}$. Anthropometric variables and adiposity had secondary, but statistically significant, effects on MAP FBF, FVC, and sweat loss. With respect to exercise in a warm humid environment, it was concluded that the effect of age on body temperature and sweating was negligible compared to effects related to $\dot{V}O_{2\,max}$, but that chronological age had an independent effect on cardiovascular effector responses.

Key words Temperature regulation - sweating - skin blood flow - exercise - aging

2.1 Introduction

Age is often used as a screening criterion for determining the capability of individuals to perform certain tasks in hot environments. Likewise, epidemiological research has shown a higher incidence of heat illness and heat related casualties in the elderly during climatic heat waves (Henschel et al., 1968). Such observations have stimulated laboratory research into the relationship between age and physiological responses to heat stress. Whereas older research has usually reported a strong adverse effect of age on heat tolerance (Hellon and Lind 1958; Hellon et al., 1956; Lind et al., 1970; Wagner et al., 1972), research over the last two decades has shown that these results were potentially confounded by population trends such as decreasing aerobic fitness (as measured by maximal oxygen uptake, $\dot{V}O_{2\,max}$) and increasing obesity which accompany the aging process. When cross-sectional designs have attempted to match different age groups with respect to physical fitness and/or body characteristics, most studies have reported no significant age difference in heat tolerance [as measured by heat storage or core temperature response (Davies 1979; Drinkwater et al., 1982; Gonzalez et al., 1980; Hellon and Lind 1958, Hellon et al., 1956; Kenney 1988; Kenney et al., 1990; Lind et al., 1970; Pandolf et al., 1988; Smolander et al., 1990; Wagner et al., 1972)], although contradictory evidence also exists (Drinkwater and Horvath 1979). And finally, there is some evidence that whether or not there is a true age difference in thermoregulatory responses to heat stress may depend on climatic factors, such as humid compared to dry heat (Kenney and Anderson 1988).

Even in studies which have noted no difference in overall heat tolerance between old and young subjects, functional differences have been observed between old and young groups in heat loss effector responses. For example, a reduced sweating capacity has been observed in older women exercising in hot dry (but not warm humid) climates (Anderson and Kenney 1987) and a reduced skin blood flow has been noted in older exercising subjects in both humid and dry environments (Anderson and Kenney 1987; Kenney 1988; Kenney et al., 1990).

Although methodologically sound, attempts to compare matched groups in a cross-section study have not yielded conclusive answers to questions of the effect of age per se for several reasons. In most studies in which various features of subjects have been matched, authors have not succeeded in matching all potentially important characteristics. Firstly, for example, matching older and younger subjects on the basis of $\dot{V}O_{2\,max}$ per kilogram body mass (Anderson and Kenney 1987; Kenney 1988) often leaves differences in absolute $\dot{V}O_{2\,max}$ of 10%-15% between groups. This often makes interpretation of results less clear. Secondly, few studies have attempted to match subjects for both $\dot{V}O_{2\,max}$ and physical activity level, two related yet independent influences on physiological responses to heat stress. And finally, it is not possible from cross-sectional designs to ascertain the relative importance of age compared to other factors (such as those associated with physical fitness, anthropometry, or body composition) in determining these responses.

The present study was designed to investigate the relative influence of age on physiological responses to (humid) heat stress during low intensity exercise. An attempt was made to determine the relative importance of age compared to other individual characteristics ($\dot{V}o_{2\,max}$, physical activity level, anthropometry, and adiposity) by multiple regression analysis. For this purpose, a subject sample was recruited which was heterogeneous with regard to relevant individual characteristics (age, $\dot{V}o_{2\,max}$, body mass, adiposity, etc.) and in which age and $\dot{V}o_{2\,max}$ were not interrelated. Furthermore, to assess the relative importance of aerobic capacity compared to those of other individual characteristics, and to draw practical conclusions about the ability of older and younger subjects to perform a fixed work task, a low intensity absolute workload of 60 W was chosen.

2.2 Methods

Location of experiments.

Experiments were performed at both the Pennsylvania State University (USA) and at the TNO Institute for Human Factors Research (The Netherlands). Experimental procedures were identical at each location. Although some equipment was different, instrument calibration and the presence of the primary author (G. Havenith) at both sites assured consistency of results.

Subjects.

Before the experiment, a power analysis was performed to determine the number of subjects needed for determination of relevant effects. For this purpose, the variance data from a previously published study using a similar exercise-heat challenge (Havenith and van Middendorp 1990) was used. That analysis determined that a minimal subject sample size of 40 would be sufficient to show significant effects on body core temperature of a magnitude of 0.1°C. A group of 73 potential subjects initially gave their voluntary and informed consent to participate in the experiment, which had been approved in advance by the respective institutional ethics review committees. Screening included a physical examination, resting 12-lead electrocardiogram (ECG), and completion of a medical history questionnaire. Each potential subject then underwent a maximal graded exercise test (GXT) on a treadmill to determine his or her $\dot{V}o_{2\,max}$, and body composition and anthropometric variables were measured. The choice for a treadmill test instead of a cycle ergometer test for determination of $\dot{V}O_{2\,max}$ was based on problems which several of the older subjects had with the high intensity cycle exercise. These subjects had never cycled before. However, after a short period they got used to the low intensity cycling exercise as used in the heat stress test (HST). A modified Balke protocol was used in the GXT; the subjects walked at a self-selected brisk pace, and after an initial 5-6 min warm-up, gradient changes of 2.5% were made every 2 min until the subject felt too fatigued to continue.

On the basis of age, $\dot{V}O_{2\,max}$ and anthropometric data, 60 of these subjects were selected to perform a standardized HST, as described below. The primary selection criterion for subject inclusion was that by adding this subject, no correlation be present in the subject group between age and $\dot{V}O_{2\,max}$, and secondarily between these variables and adiposity or anthropometric variables. This resulted in the exclusion of several young subjects who had very high $\dot{V}O_{2\,max}$ values. In addition, data from 4 subjects who were unable to finish HST were excluded from data analysis. The results of all subjects who completed HST (n = 56: 41 men and 15 women, distributed across age groups) were subsequently analysed. Their characteristics are given in Table 1.

Table 1 Values for physical and physiological characteristics of the subjects (n=56). LBM, Lean free body mass; % fat, percentage fat determined from underwater weighing; A_D = body surface area, A_D/mass = surface area/mass coefficient; $\dot{V}O_{2\,max}$ = maximal O_2 uptake

parameter	unit	mean	sd	minimum	maximum
age	(years)	44	15	20	73
$\dot{V}O_{2\,max}$	($l \cdot min^{-1}$)	3.03	0.65	1.86	4.44
	($ml \cdot kg^{-1} \cdot min^{-1}$)	42.1	7.5	27.7	56.5
	($ml \cdot kg^{-1} LBM \cdot min^{-1}$)	53.9	7	41.7	69.3
%fat	(%)	21.9	6.3	9.9	40.4
mass	(kg)	72.5	12.1	49.8	104.6
height	(cm)	173.9	7.5	157.1	192
A_D	(m^2)	1.87	0.17	1.52	2.26
A_D/mass	($m^2 \cdot kg^{-1}$)	0.026	0.002	0.021	0.031

Preliminary measurements.

During GXT, heart rate (HR, from an ECG on a recorder) and blood pressure (brachial auscultation) were measured every minute. The $\dot{V}O_{2\,max}$ was measured by open circuit spirometry using Douglas bags (USA)/Mijnhardt, Oxycon Sigma (The

Netherlands). Prior to GXT, body adiposity (percentage fat) was determined by underwater weighing (Akers and Buskirk 1969). The subjects' habitual physical activity levels (ACTIV) were assessed using a previously validated questionnaire (Ross and Jackson 1990). The ACTIV was scored on a 7-point scale, ranging from "avoid walking or exertion" (ACTIV = 0) to "run over 10 miles each week or exercise over 3 h each week" (ACTIV = 7). Body surface area (A_D) was determined from height (±0.5 cm) and mass (±20g) according to DuBois and DuBois (1916) and was also used to calculate the surface area to mass coefficient (A_D/mass).

Heat stress tests.

On a separate day, the subjects reported to the laboratory, changed into shorts (women in addition wore a standard haltertop) and had the appropriate sensors attached for HST. A venous blood sample was drawn for the determination of blood osmolality and plasma protein concentration. While these data were not used in subsequent analysis, they served to ensure that no age related differences in the state of hydration was present in the subject group. The subjects entered the environmental chamber which was controlled at a temperature of 35°C, a relative humidity of 80%, and air movement of less than 0.15 $m \cdot s^{-1}$. The subjects initially rested for 30 min in a semi-reclining chair mounted behind a cycle ergometer [Monark (USA)/Lode (The Netherlands)]. After this equilibration period they exercised on the cycle ergometer at a pedalling frequency of 60 rpm at an intensity of 60 W external resistance. The exercise period lasted 60 min, or until one of the following safety limits was reached: rectal temperature (T_{re}) was greater than 39°C, HR was greater than 90% of the individual's maximal HR as determined during GXT, or adverse symptomology. During the 90-min period in the environmental chamber, measurements were recorded on-line using Keithley (USA) and Fluke (The Netherlands) data acquisition systems, respectively, and stored on a computer at 60-s intervals.

The following variables were measured during HST: T_{re} (YSI Series 400/700 flexible thermistors inserted 12-cm beyond the anal sphincter), mean skin temperature [T_{sk}, surface-weighted average of 4 type-T thermocouples (USA) or YSI 700-series thermistors (The Netherlands) placed on the arm, upper leg, chest and back], oxygen uptake ($\dot{V}O_2$) [from analysis of expired air collected during two 2-min periods (after 15 min and after 45 min of work)], HR (ECG using a CM5 lead), forearm blood flow (FBF, venous occlusion plethysmography with a mercury-in-Silastic strain gauge; Whitney 1953), and arterial blood pressure (brachial auscultation).

Sweat loss was determined from nude body mass (±10 g accuracy) obtained before and after HST. Mass loss was not corrected for respiratory losses or metabolic exchange, as the potential contribution of these mechanisms was deemed to be constant and equal for all subjects, due to the fixed metabolic load.

In addition, the following variables were calculated: mean arterial blood pressure (MAP, in mmHg) was calculated as:

$$MAP = (0.67 \cdot \textit{diastolic pressure}) + (0.33 \cdot \textit{systolic pressure})$$

and forearm vascular conductance (FVC, in units of ml·100 $ml^{-1} \cdot min^{-1} \cdot mmHg^{-1}$) as:

$$FVC = \frac{FBF}{MAP}$$

Heat storage (S, in $J \cdot g^{-1}$) was calculated according to the equation:

$$Storage = c_b\left[0.8(T_{re} - 37) + 0.2(T_{sk} - 33)\right] \qquad (J \cdot g^{-1})$$

where c_b is the specific heat of body tissues (= 3.49 $J \cdot g^{-1} \cdot {}^{\circ}C^{-1}$).

Statistics.
Data from the final 3-min of HST were averaged and used for the statistical analysis. The multiple (non)linear regression and analysis of variance modules of the package SYSTAT (Wilkinson 1990) were used. Data were tested for normality of distribution using skewness and kurtosis calculations. The regression analysis was performed stepwise in an interactive manner. The order of the steps was determined by the investigator, based on statistical as well as physiological relevance. Significance levels of $p<0.05$ were accepted. Details about the statistical procedure have been reported previously (Havenith and van Middendorp 1990).

2.3 Results

Correlations between age and $\dot{V}O_{2\,max}$ and age and adiposity for the 56 subjects are given in Fig. 1, illustrating that these major variables were not significantly correlated. Neither were the correlations between $\dot{V}O_{2\,max}$ and adiposity significant. Further, observed values for skewness and kurtosis for the present data set indicated that the data were normally distributed. Thus the requirements for the use of multiple linear regression analysis were met for this sample of 56 subjects.

Though a range in hydration states was observed in the subject population [mean plasma osmolality 285 (SD 6) $mosmol \cdot kg^{-1}$; mean plasma protein concentration 6.64 (SD 0.29) $g \cdot dl^{-1}$] no correlation was observed between either of these variables and age. At the chosen exercise intensity of 60 W, the resulting mean $\dot{V}O_2$ was 1.09 (SD 0.12) $l \cdot min^{-1}$.

The results of the stepwise regression analysis are described below for each of the following dependent variables: T_{re}, S, HR, MAP, FBF, FVC, and sweat loss.

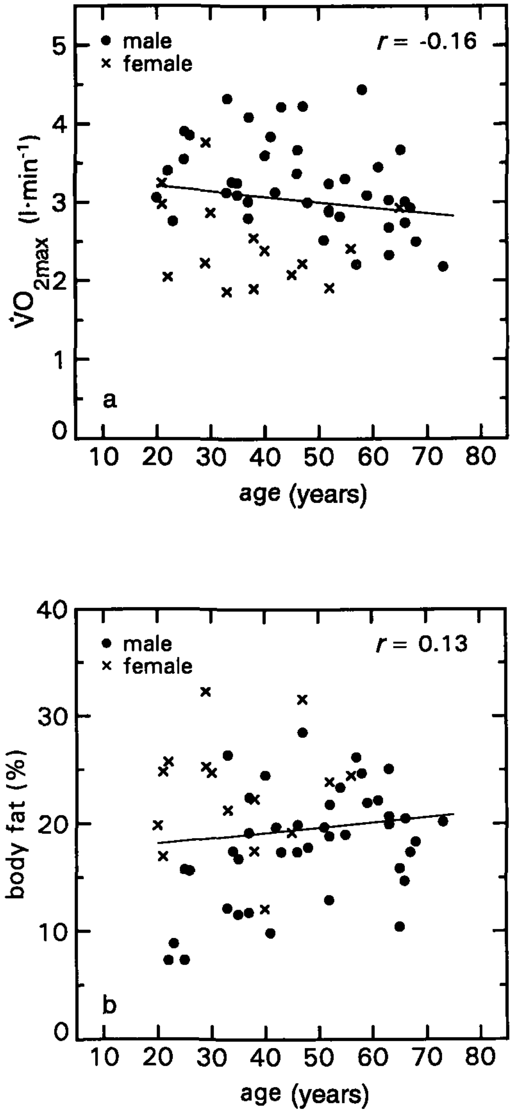

Fig. 1 The relationship between maximal oxygen uptake ($\dot{V}O_{2\,max}$) and age (a) and adiposity (%body fat) and age (b) for the 56 subjects tested. Each point represents 1 subject. Neither correlation was statistically significant, as shown by the low r values

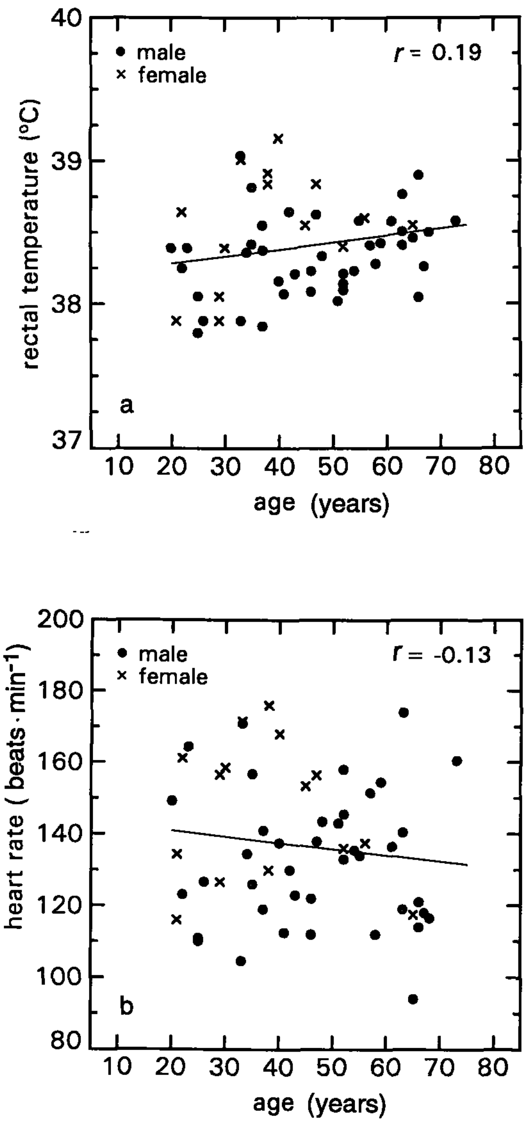

Fig. 2 Final values of rectal temperature (a) and heart rate (b) during the heat stress test as a function of age. Each point represents 1 subject

Rectal temperature and heat storage

There were no significant correlations between the final T_{re} and age (r = 0.19; Fig. 2a), adiposity (r = 0.24), or ACTIV (r = -0.10). The T_{re} was significantly correlated with absolute $\dot{V}O_{2max}$ (r = -0.50, p<0.001) and with several anthropometric measurements [A_D (r = -0.34), height (r = -0.29), mass (r = -0.30), and A_D/ mass (r = 0.29)]. Once

$\dot{V}O_{2\,max}$ was entered into the regression equation to predict T_{re}, none of the other variables had any significant correlation with the residual variance in the T_{re} data. That is, once the T_{re} response was corrected for the $\dot{V}O_{2\,max}$ effect, no other variable had a significant effect (all correlation coefficients less than 0.15 and p values greater than 0.35). The resulting regression equation was:

$$T_{re}\ (°C) = 39.16 - 0.25 \cdot VO_{2\,max}\ (in\ l \cdot min^{-1}) \qquad (r = 0.51,\ p < 0.001)$$

Similar to T_{re}, S was a significant function of $\dot{V}O_{2\,max}$ (r = -0.50, p<0.001) and anthropometric measurements (A_D, height, mass, and A_D/mass; r = -0.37, 0.29,-0.34, and 0.34, respectively). After $\dot{V}O_{2\,max}$ was entered, no other variable explained any additional variance. The equation relating S to $\dot{V}O_{2\,max}$ was:

$$S\ (J \cdot g^{-1}) = 7.9 - 0.77 \cdot VO_{2\,max}\ (in\ l \cdot min^{-1}) \qquad (r = 0.50,\ p < 0.001)$$

Sweat loss

The variables associated with the magnitude of sweat lost during HST were $\dot{V}O_{2\,max}$ (r = 0.41, p<0.01), A_D/ mass (r = 0.28, p<0.05), A_D (r = 0.40, p<0.01), body mass (r = 0.45, p<0.001), and ACTIV (r = 0.32, p < 0.05). The two regression equations generated were:

$$sweat\ loss\ (g) = -216. + 10.8 \cdot mass + 55. \cdot ACTIV \qquad (r = 0.58,\ p < 0.001)$$

and

$$sweat\ loss\ (g) = -420. + 210. \cdot VO_{2\,max} + 19.2 \cdot \%fat + 40. \cdot ACTIV$$

$$(r = 0.61,\ p < 0.001)$$

When sweat loss per metre squared A_D was used as the dependent variable, correlations were only present with ACTIV (r = 0.38, p<0.01) and $\dot{V}O_{2\,max}$, with the latter expressed per kilogram of fat free body mass (r = 0.26, p<0.05). After activity level was entered, only adiposity showed a significant correlation with the residuals (r = 0.26, p<0.05). The best equation was:

$$sweat\ loss\ (g \cdot m^{-2}) = 169. + 33.4 \cdot ACTIV + 5.4 \cdot \%fat \qquad (r = 0.45,\ p = 0.003)$$

Table 2 Partial correlation coefficients (with respective p values) for the relationship between heart rate and individual parameters. The values listed under Steps 2 and 3 are *r* values for the correlations of the residual variance for those variables once the first (and, in the case of Step 3, the second) parameters are entered into the equation. ACTIV = activity levels; other definitions see Table 1

Step:	**1**		**2**		**3**	
	r	p	*r*	p	*r*	p
$\dot{V}O_{2\,max}$ ($l \cdot min^{-1}$)	-0.66	($p<0.001$)				
age (yr)	-0.18	($p=0.19$)	-0.34	($p<0.01$)		
ACTIV (scale units)	-0.28	($p<0.05$)	-0.11	($p=0.43$)	-0.09	($p=0.54$)
%fat (%)	0.36	($p<0.01$)	0.16	($p=0.26$)	0.3	($p<0.05$)
A_D (m^2)	-0.44	($p<0.001$)	-0.01	($p=0.92$)	0.23	($p=0.10$)
mass (kg)	-0.38	($p<0.01$)	0.02	($p=0.91$)	0.3	($p<0.05$)
A_D/mass ($m^2 \cdot kg^{-1}$)	0.35	($p<0.01$)	0.05	($p=0.71$)	-0.23	($p=0.10$)

Heart rate

The relationship between maximal HR (HR_{max}) and age is well known. For the present study, the relationship between HR_{max} during GXT and age was found to be

$$HR_{max}\ (beats \cdot min^{-1}) = 210. - 0.56 \cdot age\ (years) \qquad (r=0.66,\ p<0.001)$$

No additional variables added to the explained variance in the equation. Correlation coefficients for final HST HR and the independent variables are given in Table 2. The observed HR at the end of HST correlated best with $\dot{V}O_{2\,max}$. Poorer but still significant correlations were present with ACTIV and with the anthropometric measurements. No significant correlation was present with age (Fig. 2b). As the highest correlation was present with $\dot{V}O_{2\,max}$, this variable was entered into the equation first, yielding the relationship:

$$HR\ (beats \cdot min^{-1}) = 198. - 20.2 \cdot VO_{2\,max}\ (l \cdot min^{-1}) \qquad (r=0.66,\ p<0.001)$$

The residual variance in HR corrected for the $\dot{V}O_{2\,max}$ influence was correlated only with age (Table 2, step 2). This resulted in:

$$HR\ (beats \cdot min^{-1}) = 216. - 21.3 \cdot VO_{2\,max} - 0.32 \cdot age \qquad (r=0.71,\ p<0.001)$$

As no relationship between HR and age was present in the first step, this suggested the presence of an interaction between age and $\dot{V}O_{2\,max}$ for HR. Subsequent analysis of this interaction demonstrated that, despite its presence in these data, its contribution was smaller than that of the two main effects.

After correcting for $\dot{V}O_{2\,max}$ and age, the residual variance in HR still showed a significant correlation with percentage fat and body mass (Table 2, step 3). For both correlations, the residual variance was almost equal, but body mass had the highest correlation with the variables already in the equation. This intercorrelation of parameters also explained the sign change of the correlation coefficient for body mass between steps 1 and 3. Therefore, to minimize multiple co-linearity in the model, body fat content was chosen as the variable to enter:

$$HR\ (beats{\cdot}min^{-1}) = 195. - 18.2 \cdot VO_{2\,max} - 0.46 \cdot age + 0.78 \cdot \%fat$$

$$(r = 0.74,\ p < 0.001)$$

After this step, no additional variables added significantly to the model.

As HR_{max} changes with age, we also examined the final HST HR as a percentage of each subject's maximum (% HR_{max}). The highest predictive value for $\%HR_{max}$ was provided by $\dot{V}O_{2\,max}$ (r = -0.71, p<0.001). The residual variance still showed a correlation with remaining variables, with body mass having the highest correlation (r = 0.34, p<0.01). The resulting equation was:

$$\%HR_{max} = 97.3 - 13.5 \cdot VO_{2\,max} + 0.25 \cdot mass \qquad (r = 0.76,\ p < 0.001)$$

and none of the remaining variables explained any additional variance.

Mean arterial pressure

There was a significant correlation between MAP at the end of HST and the following variables: $\dot{V}O_{2\,max}$ expressed per kilogram of body mass (r = -0.55, p<0.001), age (r = 0.58, p<0.001), adiposity (r = 0.44, p<0.001), mass (r = 0.48, p<0.001), A_D (r = -0.37, p<0.01), and A_D /mass(r = -0.60, p<0.001). After entering A_D /mass, the residual variance still correlated with adiposity, age, $\dot{V}O_{2\,max}$ per kilogram, and mass. The best complete predictive equation was produced by entering A_D/mass coefficient, age and $\dot{V}O_{2\,max}$ per kilogram:

$$MAP\ (mm\,Hg) = 165. - 2334.\frac{A_D}{mass} - 0.495\,(VO_{2\,max}kg^{-1}) + 0.167\,age$$

$$(r = 0.73,\ p < 0.001)$$

FBF and FVC

In almost every instance, the FBF value measured at the end of the test was the maximal value for the entire HST. Final FBF was significantly correlated with the same variables as MAP: $\dot{V}O_{2\,max}$ per kilogram body mass (r = 0.54, p<0.001), age (r = -0.57, p<0.001), adiposity (r = -0.45, p<0.001), and A_D/mass (r = 0.26, p<0.05). The results for regression of FBF and FVC were similar. The $\dot{V}O_{2\,max}$ per kilogram (r = 0.59, p<0.001), age (r = -0.63, p<0.001), adiposity (r = -0.49, p<0.001) and A_D/mass (r = 0.40, p<0.01) showed significant correlations, to which a significant effect of mass (r = 0.30, p<0.05) was added. For each of these cardiovascular variables, two regression formulas were deduced, and both include the age variable. Both regressions are presented for each dependent variable because:

1. The explained variance is similar for each equation,
2. The partial correlation coefficients for the independent variables are similar, and
3. Each is reasonable from a physiological perspective.

Therefore there is no statistical reason to exclude one in favour of the other.

$$FBF\ (ml \cdot 100\,ml^{-1} \cdot min^{-1}) = 10.9 - 0.17 \cdot age + 0.28 \cdot (VO_{2\,max} \cdot kg^{-1})$$

$$(r = 0.65,\ p < 0.001)$$

$$FVC\ (ml \cdot 100ml^{-1} \cdot min^{-1} \cdot mmHg^{-1}) = 0.113 - 0.0027 \cdot age + 0.0043 \cdot (VO_{2\,max} \cdot kg^{-1})$$

$$(r = 0.71,\ p < 0.001)$$

$$FBF\ (ml \cdot 100ml^{-1} \cdot min^{-1}) = 30.4 - 0.21 \cdot age - 0.29 \cdot \%fat \qquad (r = 0.63,\ p < 0.001)$$

$$FVC = 0.45 - 0.0032 \cdot age - 0.0045 \cdot \%fat \qquad (r = 0.70,\ p < 0.001)$$

A diagram of the relationship between FVC and both age and $\dot{V}O_{2\,max}$ is given in Fig. 3.

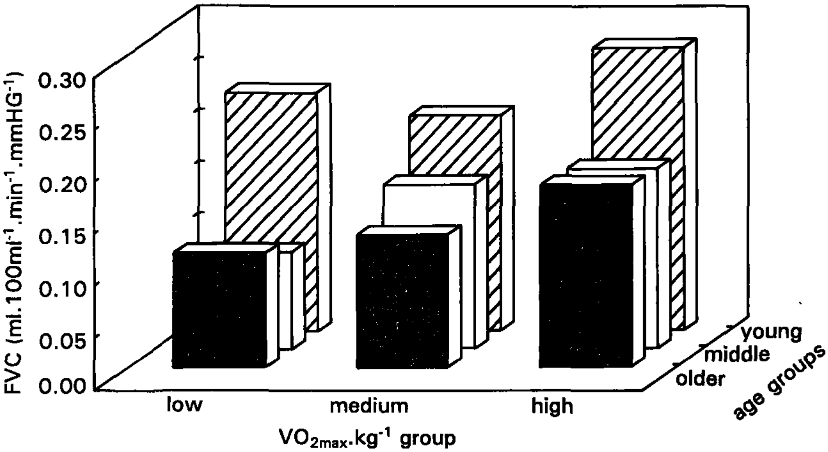

Fig. 3 The relationship of forearm vascular conductance (FVC) to maximal O_2 uptake ($\dot{V}O_{2\,max}$) per kilogram body mass and age. For illustrative purposes only, the subjects were divided into three age and three $\dot{V}O_{2\,max}$ groups. Mean values were as follows: young = 30 years, middle = 44 years, older = 63 years; low $\dot{V}O_{2\,max}$ = 33.9, medium = 42.7, and high = 51.8 ml · min^{-1} · kg^{-1}

Non-linear effects of age

For some of the variables studied, analysis of the effect of age revealed nonlinear components. Significant non linear effects were observed for effects of age on HR_{max}, HR, FBF and FVC, such that inclusion of a second order effect of age improved the regression equations. This resulted in the following equations:

$$HR_{max} = 199. - 0.0063 \cdot age^2 \qquad (r=0.67,\ p<0.001)$$

$$HR = 165. - 19.5 \cdot VO_{2\,max} + 1.54 \cdot age - 0.022 \cdot age^2 + 0.48 \cdot \%fat$$

$$(r=0.76,\ p<0.001)$$

$$FBF = 23. + 0.26 \cdot (VO_{2\,max} \cdot kg^{-1}) - 0.72 \cdot age + 0.006 \cdot age^2 \qquad (r=0.68,\ p<0.001)$$

$$FVC = 0.331 + 0.004 \cdot (VO_{2\,max} \cdot kg^{-1}) - 0.013 \cdot age + 0.001 \cdot age^2$$

$$(r=0.75,\ p<0.001)$$

2.4 Discussion

Though, based on data from the literature some of the observed effects may have been expected a priori, the simultaneous study of these effects as used in the present study provides a more integrated knowledge of the relevant relationships. Most recent studies of the effects of age on physiological responses have attempted to match groups of old and young subjects for one or more characteristics, thus isolating age as a discrete independent variable. The present investigation differed in its approach, testing a larger subject sample which was heterogeneous for several potentially important physical and physiological subject characteristics, of which age was only one. The results suggest that age is an important contributory factor in cardiovascular effector responses to a humid HST, in particular, for HR and skin blood flow (both lower with advancing age). On the other hand, thermoregulatory (S, core temperature) and sweating responses are more closely related to $\dot{V}O_{2\,max}$ and physical activity level. Once these variables are accounted for, there is no significant effect of age. Anthropometric measurements and body composition have significant, but secondary, influences on the physiological responses measured here.

Comments on the methodology

As the approach used in the present study is quite different from most research in this area, some comments seem appropriate. As the aim of the study was to determine relative effects of individual characteristics, several choices were made which may seem in contradiction to what is commonly accepted in this field of research. Choosing a fixed exercise intensity resulted in different relative intensities (percentage $\dot{V}O_{2\,max}$) for subjects (though equal among age groups) resulting in different thermal loads. However, using relative intensities (equal percentage $\dot{V}O_{2\,max}$) would correct the results for differences in aerobic capacity among subjects and it would become impossible to determine the relative importance of aerobic capacity compared to that of, for example, age or percentage body fat. Also for the regression analysis single parameters ($\dot{V}O_{2\,max}$) were preferred to combined ones (percentage $\dot{V}O_{2\,max}$, $\dot{V}O_{2\,max}$ per kilogram) which are usually preferred for analysis. The latter includes two body characteristics at once, and corrects data for the effect of differences in body mass. However, the aim of the regression analysis is to separate these effects and to determine their relative influence.

Instead of comparing two disparate age groups, subjects spanning a continuum of age were studied. Subject selection was restricted such that the average values for each age group's (for example by decade) physical characteristics should not differ, but that a wide range of each characteristic would be present in these data. Hence, in the present study subject groups differing in age had a similar average $\dot{V}O_{2\,max}$, adiposity, etc., but a large variation was present within each age group.

The subject sample tested here reflected neither the age-related decline in $\dot{V}O_{2\,max}$ (Hodgson and Buskirk 1977) nor the changes in body height, mass, or adiposity inherent in the overall population. Thus, observed results do not reflect a typical population response, but reflect functional relationships between chronological age and other body characteristics. A second potential disadvantage of this methodology is that the large variance introduced into the test group could have resulted in a larger variance in the results, diminishing the significance of any effects. However, in those independent variables which had practical relevance for heat stress responses, a significant effect should still have been observed. (This was supported by the results of the a priori power analysis.)

However, there are distinct advantages in this study design which outweigh the required statistical constraints. Firstly, the large intra-group variance allows for the analysis of the relative contribution of these variables relative to other variables. To analyse this type of data, the assumption has to be made that the variables should not show any significant correlation among each other. As shown in part in Fig. 1, this assumption was met, except for a weak but insignificant correlation between adiposity and $\dot{V}O_{2\,max}$. However, regressions in which both variables are present should be treated with caution.

Secondly, having a continuous age scale available in the population allows for analysis of possible nonlinear effects of age on the heat stress responses. Thirdly, the current approach eliminates the various problems encountered in trying to match two or more discrete age groups with respect to all potentially important contributory factors. The need to match subjects for $\dot{V}O_{2\,max}$ in age research on thermoregulation is particularly acute. For work within a wide range of ambient conditions (termed the "prescriptive zone"), body core temperature has been shown to be closely related to the exercise intensity expressed as a percentage of the individual $\dot{V}O_{2\,max}$ (Lind et al., 1970). However, in experiments performed with old and young groups working at equal relative intensities, absolute exercise intensities were sometimes dramatically different (Davies 1981; Lind et al., 1970; Vroman et al., 1983; Yousef et al., 1984). Since sweating rate is related to absolute exercise intensity (as is absolute metabolic heat production) subjects need to exercise at the same absolute and relative intensities to compare thermoregulatory responses to the same stimuli, a situation which can only be accomplished if $\dot{V}O_{2\,max}$ is similar among age groups. This sets up a comparison of fitter than average older subjects with more sedentary younger subjects (Pandolf et al., 1988).

Together with changes in $\dot{V}O_{2\,max}$, body mass, size, and composition also change with age. These effects, confounded with age, have been found to be magnified when work is weight-bearing, such as uphill treadmill walking or stepping (Smolander et al., 1990). Alternatively, when subject group fitness is matched by comparing age groups with a *similar mean* $\dot{V}O_{2\,max}$ per kilogram of body mass, it has been found that differences in absolute $\dot{V}O_{2\,max}$ are often considerable (Anderson and Kenney 1987; Davies 1981; Drinkwater et al., 1977; Kenney 1988; Smolander et al., 1990). Finally, other physical characteristics, such as the surface area/mass coefficient, may also be important because of their direct effect on heat production and exchange. Only when subjects are matched for all characteristics which affect their physiological responses can the effects of age per se be delineated with any degree of clarity.

To our knowledge, the present approach to analysing heat stress responses has not previously been used. A similar technique has been used to look at maximal work capacity as a function of such variables as age, mass, adiposity, smoking behaviour, vital capacity, resting HR and activity level (Bovens et al., 1993). The explained variance in maximal work capacity due to age was 50%. The significant presence of age in that predictive equation may be explained by the epidemiological nature of the study, with older subjects being less fit.

A further important point which should be addressed is the inclusion of women in the set of data without consideration of a specific sex effect. Havenith and van Middendorp (1990), using a similar technique as the present, have shown that when the physical characteristics of both sexes are included in the analysis of heat stress response, no specific sex differences are observed during work in the heat. The lack of a distinct sex influence on responses to heat stress is well known (for a review, see Kenney 1985). A separate analysis of the set of data for the men only (3 subjects excluded to prevent correlation of $\dot{V}O_{2\,max}$ and age) produced similar results as the present set of data. However, due to the limited ranges in, for example, percentage fat and the smaller set of data, determination of relative influences of parameters was more difficult.

Heat strain and thermoregulatory responses

In the present experiment, with its large inter-individual variance in physical and physiological characteristics, no effect of age on either body temperature or S was observed. If body core temperature is accepted as the most important variable in determining heat tolerance, no age effect on heat tolerance is present. The notion that core temperature is the critical factor in heat tolerance, that is superseding possible cardiovascular failure, has been the underlying assumption used by a variety of organizations (ISO 1993; NIOSH 1986) to set heat stress standards for industry and the military. This assumption has been supported by recent observations of Nielsen et al., (1993), although their subjects were very well-trained athletes.

A high level of cardiorespiratory function may easily mask limitations of performance in HST which are of a circulatory nature.

Although evaporative heat loss was limited in this humid environment, sweat loss over the session represented another unique thermoregulatory effector response. Whether expressed as absolute mass lost or corrected for A_D, there was no significant relationship between sweating and age. It has been stated that sweating rate is a function of absolute exercise intensity (Drinkwater and Horvath 1979); however, there is a large degree of inter-individual variability in sweating responses at a given absolute intensity, as demonstrated in the present experiment. Sweat loss was significantly related to such variables as $\dot{V}O_{2\,max}$, body fat content (or body mass), and regular ACTIV.

Sweat loss per metre squared A_D (which has greater thermoregulatory relevance) was most strongly related to the subjects' ACTIV. There is a clear distinction between the $\dot{V}O_{2\,max}$ and ACTIV, since the former has an inherent genetic component. While both are undoubtedly important in determining sweating rate under a variety of conditions, there is another explanation for the dominance of ACTIV in predicting sweat loss. Regular exercise, in addition to causing an increase in $\dot{V}O_{2\,max}$, has also been found to confer a higher level of heat acclimation (Henane et al., 1977). The increased core temperature in exercise raises the central stimulus to the sweat glands, and the concomitant increase in T_{sk} directly affects the sweat glands. The result is an increase in gain of the sweat rate-core temperature relationship, representing the improvement in the individual's acclimation status (Havenith and van Middendorp 1990). Pandolf et al., (1988) and Kenney et al., (1990) have both suggested that older subjects by necessity have a higher regular activity level than younger subjects of equal $\dot{V}O_{2\,max}$, and therefore have a higher level of acclimation. In the present experiment, this hypothesis was tested by recording and analysing ACTIV of all subjects. No correlation was present between ACTIV and age in the present set of data. The ACTIV was not a significant predictor of any variable other than sweat loss.

Cardiovascular responses

Unlike thermoregulatory variables, age played a significant role in determining all cardiovascular variables measured during HST (i.e. final HR, MAP, FBF, and FVC). The (inverse) effect of age on HR was lost, however, when HR was expressed as the individual's $\%HR_{max}$. This measure of cardiac strain, was related to $\dot{V}O_{2\,max}$ across the age groups.

As suggested by Kenney et al., (1990), effects of age on circulatory variables may be secondary to age-related changes in hydration status. Observed increases in blood osmolality with age (O'Neill et al., 1990; Spangler et al., 1984) may indicate acute or chronic hypohydration. Since it has been shown that hydration state, independent of $\dot{V}O_{2\,max}$ or age, may profoundly influence the cardiovascular response to HST (Fortney et al., 1984; Nadel et al., 1980; O'Neill et al., 1990; Spangler et al., 1984), we chose to pre-screen the subjects in the present study by determining plasma osmolality and plasma protein concentration. Osmolality and plasma protein values were obtained from 46 subjects ranging in age from 30 to 73 years. Neither of these variables was related to age, excluding the possibility of contamination of the results by alterations in hydration state.

The reduced peripheral blood flow responses (lower FBF and FVC) with age, accompanied by unchanged core temperature, have previously been reported by Kenney (Fortney et al., 1984; Kenney 1988; Kenney et al., 1990,1991; Nadel et al., 1980; O'Neill et al., 1990; Spangler et al., 1984) and discussed by Kenney and Havenith (1993). At a given core temperature, FBF and FVC were lower in the older subjects as a result of a lower slope of the FBF : core temperature response once vasodilation has begun (Kenney 1988). Since $\dot{V}O_{2\,max}$ plays a large role in determining core temperature (as shown by the T_{re} data in the present study) it is not surprising that both age and $\dot{V}O_{2\,max}$ are significant predictors of FBF and FVC (Fig. 3). In the warm humid climate chosen for the present experiment, in which both dry and evaporative heat loss are minimal, the effect of a reduced skin blood flow on core temperature is likewise minimal.

Vroman et al., (1983) have suggested that adiposity also played a role in determining the skin blood flow response to an exercise-heat challenge. It is noteworthy that while age remains as a significant predictor with approximately the same influence on FBF and FVC, substituting adiposity for $\dot{V}O_{2\,max}$ does not weaken or strengthen the regression. The combined effects of age and $\dot{V}O_{2\,max}$ or age and percentage body fatness each explain 40%-50% of the variance in FBF and FVC.

The observed nonlinear effects of age on cardiovascular variables HR_{max}, HR, FBF and FVC show that reductions in HR_{max} and final HST HR become stronger with advancing age, whereas the strongest reduction in maximal FBF and FVC appears to occur before the age of 45 years. This would suggest that age-related changes in HR_{max} and in peripheral vasodilatation are independent processes.

In summary, stepwise regression analysis was used to determine what physical and physiological characteristics were important predictors of physiological responses to exercise in a warm, humid climate. Age (in the range of 20-73 years) had significant effects on central (HR) and peripheral (MAP, FBF, FVC) cardiovascular responses. On the other hand, age had no significant effect on body temperature, S, sweat loss or on HR expressed as percentage of the individual's maximum, all of which were closely related to $\dot{V}O_{2\,max}$ (and in the case of sweating, physical activity level).

Acknowledgements The authors gratefully acknowledge the medical screening assistance of Dr W.C. Nicholas, D. Campolongo, R.N., Dr J.R. Krol, and Dr M.R. Simons, the technical assistance of M. Druckenmiller, D. Johnson, J. Loomis and F. Weyandt, assistance with the power analysis of C.W. Coakley and J. Derr, and the assistance during the experiments of A. Ehman, D. Mikita, T.G.M. Vrijkotte and L.J.A. Wammes.

References

Akers RF, Buskirk ER (1969) *An underwater weighing system utilizing "force cube" transducers.* J Appl Physiol 26:649652

Anderson RK, Kenney WL (1987) *Effect of age on heat-activated sweat gland density and flow during exercise in dry heat.* J Appl Physiol 63:1089-1094

Bovens AMPM, van Baak MA, Vrencken JGPM, Wijnen JAG, Saris WHM, Verstappen FTJ (1993) *Maximal aerobic power in cycle ergometry in middle aged men and women active in sports, in relation to age and physical activity.* Int J Sports Med 14: 66-71

Davies CTM (1979) *Thermoregulation during exercise in relation to sex and age.* Eur J Appl Physiol 42:71-79

Davies CTM (1981) *Thermal response to exercise in children.* Ergonomics 24:55-61

Drinkwater BL, Horvath SM (1979) *Heat tolerance in aging.* Med Sci Sports Exerc 11:49-55

Drinkwater BL, Bedi JF, Louks AB, Roche S, Horvath SM (1982) *Sweating sensitivity and capacity of women in relation to age.* J Appl Physiol 53:671-676

Drinkwater BL, Kupprat IC, Denton JE, Crist JL, Horvath SM (1977) *Response of prepubertal girls and college women in the heat.* J Appl Physiol 43:1046-1053

DuBois D, DuBois EF (1916) *Clinical calorimetry: a formula to estimate the appropriate surface area if height and weight be known.* Arch Int Med 17:863-871

Fortney SM, Wenger CB, Bove JR, Nadel ER (1984) *Effect of hyperosmolality on control of blood flow and sweating.* J Appl Physiol Respir Environ Exerc Physiol 57:1688-1695

Gonzalez RR, Berglund LG, Stolwijk JAJ (1980) *Thermoregulation in humans of different ages during thermal transients.* In: Szélenyi Z, Székely M (eds). Proceedings of Satellite of 28th International Congress of Physiol. Sci. Pecs, vol 32. Pergamon Press, Oxford and Akademia Kiado, Budapest

Havenith G, van Middendorp H (1990) *The relative influence of physical fitness, acclimation state, anthropometric measures and gender on individual reactions to heat stress.* Eur J Appl Physiol 61:419-427

Hellon RF, Lind AR (1958) *The influence of age on peripheral vasodilation in a hot environment.* J Physiol (Lond) 141: 262

Hellon RF, Lind AR, Weiner JS (1956) *The physiological reactions of men of two age groups to a hot environment.* J Physiol (Lond) 133:118-131

Henane R, Flandrois R, Charbonnier JP (1977) *Increases in sweating sensitivity by endurance conditioning in man.* J Appl Physiol 43: 822-828

Henschel A, Cole MB, Lyczkowskyj O (1968) *Heat tolerance of elderly persons living in a subtropical climate.* J Gerontol 23:17-22

Hodgson JL, Buskirk ER (1977) *Physical fitness and age, with emphasis on cardiovascular function in the elderly.* J Am Geriatr Soc 25: 385-392

ISO (1993) *Ergonomics of the thermal environment. Medical supervision of individuals exposed to hot or cold environments.* International Organization for Standardization, Geneva, ISO CD 12894

Kenney WL (1985) *A review of comparative responses of men and women to heat stress.* Environ Res 37:1-11

Kenney WL (1988) *Control of heat-induced vasodilation in relation to age.* Eur J Appl Physiol 57:120-125

Kenney WL, Anderson RK (1988) *Responses of older and younger women to exercise in dry and humid heat without fluid replacement.* Med Sci Sports Exerc 20:155-160

Kenney WL, Havenith G (1993) *Heat stress and age-skin blood flow and body temperature.* J Thermal Biol 19:341-344

Kenney WL, Tankersley CG, Newswanger DL, Hyde DE, Puhl SM (1990) *Age and hypohydration independently influence the peripheral vascular response to heat stress.* J Appl Physiol 68: 1902-1908

Kenney WL, Tankersley CG, Newswanger DL, Puhl SM (1991) *Alpha 1 adrenergic blockade does not alter control of skin blood flow during exercise.* Am J Physiol 260:H855-H861

Lind AR, Humphreys PW, Collins KJ, Foster K, Sweetland KF (1970) *Influence of age and daily duration of exposure on responses of men to work in heat.* J Appl Physiol 28:50-56

Nadel ER, Fortney SM, Wenger CB (1980) *Effect of hydration state on circulatory and thermal regulations.* J Appl Physiol Respir Environ Exerc Physiol 49:715-721

Nielsen B, Hales JRS, Strange S, Juel Christensen N, Warburg J, Saltin B (1993) *Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot dry environment.* J Physiol (Lond) 460:467-485

NIOSH (National Institute for Occupational Safety and Health) (1986) *Occupational exposure to hot environments.* Revised criteria. U.S. Dept. of Health and Human Services, Washington, D.C., Publication no. 86-113, 140

O'Neill PA, Faragher EB, Davies I, Wears R, McLean KA, Fairweather DS (1990) *Reduced survival with increasing plasma osmolality in elderly continuing care patients.* Age Ageing 19: 68-71

Pandolf KB, Cadarette BS, Sawka MN, Young AJ, Francesconi RP, Gonzalez RR (1988) *Thermoregulatory responses of middle-aged and young men during dry-heat acclimation.* J Appl Physiol 65:65-71

Ross, AM, Jackson AS (1990) *Exercise concepts, calculations and computer applications.* Benchmark Press, Carmel, Ind.

Smolander J, Korhonen O, Ilmarinen R (1990) *Responses of young and older men during prolonged exercise in dry and humid heat.* Eur J Appl Physiol 61: 413-418

Spangler PF, Risley TR, Bilyew DD (1984) *The management of dehydration and incontinence in non-ambulatory geriatric patients.* J Appl Behav Anal 17:397-401

Vroman NB, Buskirk ER, Hodgson JL (1983) *Cardiac output and skin blood flow in lean and obese individuals during exercise in the heat.* J Appl Physiol Respir Environ Exerc Physiol 55: 69-74

Wagner JA, Robinson S, Tzankoff SP, Marino RP (1972) *Heat tolerance and acclimatization to work in the heat in relation to age.* J Appl Physiol 33:616-622

Whitney RJ (1953) *The measurement of volume changes in human limbs.* J Physiol (Lond) 121: 1-27

Wilkinson L (1990) *SYSTAT: the system for statistics.* Systat, Inc., Evanston, Ill.

Yousef MK, Dill DB, Vitez TF, Hillyard SD, Goldman AS (1984) *Thermoregulatory responses to desert heat: age, race and sex.* J Gerontol 39:406-414

3

The relative influence of body characteristics on humid heat stress response

Chapter 3

The relative influence of body characteristics on humid heat stress response

George Havenith · Viktor G.M. Luttikholt · Tanja G.M. Vrijkotte

(European Journal of Applied Physiology, 70:270-279, 1995)

Summary The present study was designed to determine the relative importance of individual characteristics such as maximal oxygen uptake ($\dot{V}O_{2\,max}$), adiposity, DuBois body surface area (A_D), surface to mass ratio (A_D /mass) and body mass, for the individual's reaction to humid heat stress. For this purpose 27 subjects (19 men, 8 women), with heterogeneous characteristics ($\dot{V}O_{2\,max}$ 1.86-5.28 l·min^{-1}; fat% 8.0%-31.9%; mass 49.8-102.1 kg; A_D 1.52-2.33 m^2) first rested (30 min) and then exercised (60 W for 1 h) on a cycle ergometer in a warm humid climate (35°C, 80% relative humidity). Their physiological responses at the end of exercise were analysed to assess their relationship with individual characteristics using a stepwise multiple regression technique. Dependent variables (with ranges) included final values of rectal temperature (T_{re} 37.5-39.0°C), mean skin temperature (T_{sk} 35.7-37.5°C), body heat storage (S 3.2-8.1 J·g^{-1}), heart rate (HR 100-172 beat·min^{-1}), sweat loss (397-1403 g), mean arterial blood pressure (MAP, 68-96 mmHg), forearm blood flow (FBF, 10.1-33.9 ml·100ml^{-1}·min^{-1}) and forearm vascular conductance (FVC = FBF/MAP, 0.11-0.49 ml·100ml^{-1}·min^{-1}·mmHg^{-1}). The T_{re}, T_{sk} and S were (34%-65%) determined in the main by $\dot{V}O_{2\,max}$ or by exercise intensity expressed as a percentage of $\dot{V}O_{2\,max}$ (%$\dot{V}O_{2\,max}$). For T_{re}, A_D /mass ratio also contributed to the variance explained, with about half the effect of $\dot{V}O_{2\,max}$. For T_{sk}, fat% contributed to the variance explained with about two-third the effect of $\dot{V}O_{2\,max}$. Total body sweat loss was highly dependent (50%) on body size (A_D or mass) with regular activity level having a quarter of the effect of body size on sweat loss. The HR, similar to T_{re}, was determined by $\dot{V}O_{2\,max}$ (48%-51%), with less than half the effect of A_D or A_D /mass (20%). Other circulatory parameters (FBF, MAP, FVC) showed little relationship with individual characteristics (< 36% of variance explained). In general, the higher the $\dot{V}O_{2\,max}$ and/or the bigger the subject, the lower the heat strain observed. The widely accepted concept, that body core temperature is determined by exercise intensity expressed as %$\dot{V}O_{2\,max}$ and sweat loss by absolute heat load, was only partially supported by the results. For both variables, other individual characteristics were also shown to contribute.

Key words Body temperature-Sweating-Exercise-Heat strain-Body characteristics

3.1 Introduction

Parameters which influence the heat stress response of an individual have been summarized in several reviews (Havenith 1985; Kenney 1985) comprising physical fitness, acclimatization, hydration state, drug and alcohol use, hypertension, sex, adiposity, anthropometric measurements and age. These individual parameters have seldom been incorporated in tools/models for the prediction of heat strain during work in warm climates. Prediction of heat stress and strain is an important issue in industry, as well as in military situations. Particularly during the Gulf crisis, where in addition to the climatic stress, protective clothing increased the risk of heat casualties, models predicting heat strain have proved to be of value. However, as individual differences have not been included, these models for predicting heat stress/strain (Gagge 1973; Givoni and Goldman 1973; ISO 1982, 1989; Lotens 1993) are limited to prediction of the average response, which may involve risks for individuals at the extremes of the population (Wenzel et al., 1989).

The effect of the above-mentioned individual parameters has been studied extensively, but usually looking at only one parameter at a time. Most studies have matched subjects for one or more parameters, while investigating another (Frye and Kamon 1981; Anderson and Kenney 1987; Kenney 1988). Others have used subject groups with heterogeneous parameters and analysed the relative effect of these parameters on heat stress response (Havenith and van Middendorp 1990; Havenith et al., 1993, 1995). The latter approach allowed the determination of a weighting factor for the effect of individual parameters. These weighting factors can then be used for instance to select subjects to perform a certain stressful task, or for the improvement of the simulation models. Havenith and van Middendorp (1990) have studied the relevance of the following parameters: acclimation, sex, $\dot{V}O_{2\,max}$, and the anthropometrics for exercise at a fixed percentage of an individual's $\dot{V}O_{2\,max}$ in cool, warm-humid, and hot-dry climates. In most climates, heat strain, determined by body core temperature, has been found to be related to the exercise intensity expressed as percentage of $\dot{V}O_{2\,max}$ (Åstrand 1960; Saltin and Hermansen 1966). The relative influence of the individual's aerobic power on heat strain, compared to that of other individual characteristics, may thus have been underestimated in the Havenith and van Middendorp (1990) experiment as they used relative exercise intensities. Also, as in many work environments the task load is fixed, the question arises as to what the weighting factor for the individual differences (e.g. $\dot{V}O_{2\,max}$ versus body fat%) would be if subjects had to perform a fixed absolute work load instead of a load relative to their aerobic power ($\dot{V}O_{2\,max}$). This question has been studied by Havenith et al., (1993, 1995), focusing in the main on the relative effects of age and aerobic power. To get a better assessment of the effects of individual parameters other than age, the young group (n = 12) from that experiment has been expanded. This group of subjects, heterogeneous in aerobic power, sex, adiposity, anthropometric measurements and patterns of regular activity was exposed to a warm-humid climate while performing a fixed work load on a cycle ergometer. Analysis of the data obtained should answer the question as to which of the individual characteristics are concerned with the person's reaction to heat stress, and how important these parameters are in relation to each other.

3.2 Methods

Screening

A group of 38 subjects volunteered for the study, which was approved by the Institute's Medical Ethics Committee. Before participation in the experiment the subjects signed an informed consent and were medically screened. This included a physical examination, resting 12-lead electrocardiogram (ECG), and completion of a medical history questionnaire. Each potential subject underwent a graded exercise test (GXT) on a treadmill, using a modified Balke protocol [2.5% gradient changes (= 1.23 $W \cdot kg^{-1}$ at 5 $km \cdot h^{-1}$), every 2 min after a 5 min warm-up at 5% gradient until the subject felt fatigued]. During the GXT, heart rate (HR, via CM5 lead outputted to a recorder) and blood pressure (via brachial auscultation) were obtained every minute. Maximal oxygen uptake ($\dot{V}O_{2max}$, Mijnhardt, Oxycon Sigma) during the GXT (over a 1-min period served as the measure of aerobic power. Adiposity was interpreted in two ways: firstly, as the thickness of the subcutaneous fat layer, measured as the sum of four skinfolds (Durnin and Womersly 1974) and, secondly, as total body fat percentage, determined by underwater weighing (Akers and Buskirk 1969). This separation was made to test whether sub-cutaneous fat (skinfolds) affects thermoregulation through its insulative properties or whether thermoregulation is more affected by total body fat as a passive body mass with a lower than average specific heat. The subjects' habitual physical activity was recorded using a questionnaire, describing their participation in exercise programmes, etc. (Ross and Jackson 1990). Activity level (ACTIV) was scored on a 7-point scale, ranging from "avoid walking or exertion" to "run over 10 miles each week or exercise over 3 h each week". Body surface area (A_D) was determined from height (± 0.5 cm) and mass (± 10 g) according to DuBois and DuBois (1916) and was also used to calculate the surface to mass ratio of the subjects (A_D/mass). From the group of subjects screened, 27 (19 men, 8 women) were selected to perform the heat stress test (HST). This selection was based on the need to minimize correlations between individual parameters, to analyse these as independent parameters (Havenith et al., 1995). Natural acclimatization levels of all subjects were presumed to be equal, as all tests were performed in the spring. The subjects were interviewed for possible recreational heat exposures.

Heat stress test

For HST, each subject reported to the laboratory, changed into shorts (women also with a haltertop) and had sensors attached (description below). Next they entered the climatic chamber controlled at an ambient and radiant temperature of 35°C, at a relative humidity of 80% and a wind speed below 0.2 $m \cdot s^{-1}$. The subjects rested for 30 min in a semi-reclining chair mounted behind a cycle ergometer. Next, they started to exercise (60 W) on an electrically braked cycle ergometer (Lode). They aimed at a pedalling frequency of 60 rpm. They cycled for 60 min, or until reaching one of the safety criteria [rectal temperature (T_{re}) > 39°C or HR > 90% of the individual maximum as determined] in the GXT, or any adverse symptomology). During the period in the climatic chamber on-line measurements were made, using a Fluke data acquisition system, of the following variables: T_{re} by a thermistor (Yellow springs instruments, 700 series) inserted 12 cm beyond the anal sphincter; mean skin temperature (T_{sk}), as a surface weighted average of 4 YSI 700 series thermistors placed on the arm, upper leg, chest and back; oxygen uptake ($\dot{V}O_2$) by analysis of expired gases during two 5-min periods (after 15-min and after 45-min work) using a Mijnhardt Oxycon Sigma system; HR, from CM5 lead via a recorder and oscilloscope for constant monitoring; forearm blood flow (FBF), using venous occlusion plethysmography (Whitney 1953), with temporary arterial occlusion of the hand and venous occlusion of the upper arm. Mean arterial blood pressure (MAP) was determined by brachial auscultation and calculated as:

$$MAP = \frac{(2.0 \cdot diastolic\ pressure + systolic\ pressure)}{3.0} \qquad (mmHg)$$

Forearm vascular conductance (FVC) was calculated as:

$$FVC = \frac{FBF}{MAP} \qquad (ml \cdot 100ml^{-1} \cdot min^{-1} \cdot mmHg^{-1})$$

Sweat loss was determined by weighing subjects before and after the heat exposure. Mass loss was not corrected for metabolic and respiratory mass losses, as these were assumed to be equal for all subjects due to the fixed metabolic rate.

Body heat storage (S) was calculated as:

$$S = (0.8\Delta T_{re} + 0.2\Delta T_{sk}) \cdot c_b \quad (J \cdot g^{-1})$$

with c_b as the specific heat of body tissue (= 3.49 $J \cdot g^{-1} \cdot °C^{-1}$).

Data were stored at 60-s intervals. The final statistical analysis was performed using the data from the end of the test, averaged over the last 3 min (only subjects who completed 90 min were included).

Statistics

For the statistical analysis, the multiple (non)linear regression and analysis of variance modules of the package SYSTAT (Wilkinson 1990) were used. Distributions of data were tested for normality using probability plots and skewness and kurtosis calculations. The regression analysis was performed stepwise in an interactive manner. The order of the steps was determined by the investigator, based on statistical as well as physiological relevance. Significance levels $p < 0.05$ were accepted. Outliers were determined using Studentized residuals and Cook's D-statistic.

The values presented for the variance explained in the data (r^2_{adj}) are so called "adjusted r^2" values, which take in account the number of data and the number of predictors used in the equation.

3.3 Results

Subjects

In total, data for 27 subjects (19 men, 8 women) were collected. Their individual characteristics are presented in Table 1. For the analysis, sex was coded as 1 for men and 0 for women.

Statistical constraints

The attempt to prevent intercorrelation of individual characteristics was only partially successful. As expected, $\dot{V}O_{2\,max}$ (litre per minute) among the subjects was not correlated to adiposity or skinfold thickness, but did show a significant correlation with body mass and related parameters such as A_D, lean body mass and A_D/mass. Also (by definition) anthropometric data such as mass, height, A_D and A_D/mass were inter-correlated. Thus when these parameters are present together in the equations this should be considered.

Table 1 Physical characteristics of the subjects (n = 27). $\dot{V}O_{2\,max}$ = Maximal oxygen uptake, %fat = percentage determined from under water weighing, skinfolds = sum of four skinfold thicknesses, A_D = body surface area, A_D/mass = surface to mass ratio

	Mean	SD	Minimum	Maximum
age (years)	25.7	4.5	18	35
$\dot{V}O_{2\,max}$ ($l \cdot min^{-1}$)	3.66	0.88	1.86	5.28
$\dot{V}O_{2\,max}$/kg ($ml \cdot min^{-1} \cdot kg^{-1}$)	51.3	7.9	33.1	69.2
%fat (%)	17.6	6.5	8.0	31.9
skinfolds (mm)	36.1	15.8	18.9	78.8
body mass (kg)	71.2	13.0	49.8	102.1
height (cm)	179.2	9.8	162.0	193.5
A_D (m^2)	1.89	0.20	1.52	2.33
A_D/mass ($m^2 \cdot kg^{-1}$)	0.027	0.002	0.022	0.031

Table 2 Data obtained at the end of the heat stress test (n = 27). T_{re} = Rectal temperature, T_{sk} = mean skin temperature, S = heat storage, HR = heart rate, FBF = forearm blood flow, MAP = mean arterial pressure, FVC = forearm vascular conductance, $\dot{V}O_2$ = oxygen uptake

	Mean	SD	Minimum	Maximum
T_{re} (°C)	38.12	0.38	37.54	39.04
T_{sk} (°C)	36.5	0.5	35.7	37.5
S ($J \cdot g^{-1}$)	4.8	1.3	3.2	8.1
HR (bpm)	131	22	100	172
sweat loss (g)	820	291	397	1403
FBF ($ml \cdot 100ml^{-1} \cdot min^{-1}$)	21.5	6.5	10.1	33.9
MAP (mm Hg)	80	9	68	96
FVC ($ml \cdot 100ml^{-1} \cdot min^{-1} \cdot mm\ Hg^{-1}$)	.28	.10	.11	.49
$\dot{V}O_2$ ($ml \cdot min^{-1}$)	980	63	869	1107

Physiological data

The data obtained during HST showed a large variation among subjects. This can be seen in Fig. 1 for the 2 subjects with minimal and maximal increases in T_{re} during HST. In both cases T_{re} and HR hardly changed during the rest period, but increased at the commencement of exercise. The T_{sk} on the other hand started to increase at the moment the chamber was entered. The results for the end of HST are presented in Table 2.

First order correlations of the physiological variables with the individual parameters are presented in Table 3. To provide a better understanding of the relationships, *r* values are presented by classes based on significance level instead of actual numbers.

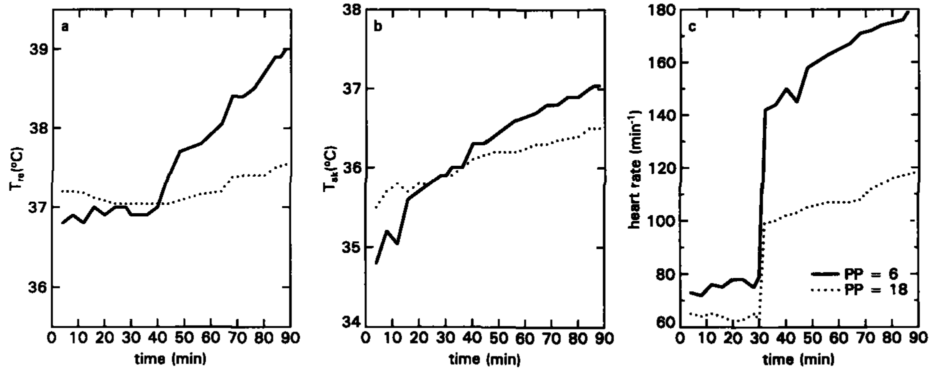

Fig. 1 Time course of (a) rectal temperature (T_{re}), (b) skin temperature (T_{sk}) and (c) heart rate at rest and during exercise during the heat stress test for the two subjects with minimal and maximal change in T_{re}

Regression analysis

In addition to the individual parameters mentioned in Table 1, some other representations of these parameters were also tested in the regression analysis. This concerns in the main the test of possible nonlinear relationships between individual parameters and heat stress responses. Of these representations only one was found to give such nonlinear contributions which were higher than those of the linear representation: this was $1/\dot{V}o_{2\,max}$. This presentation of $\dot{V}o_{2\,max}$ will therefore also be used in the following presentation of results.

Rectal temperature

The final values for T_{re} showed a good correlation with a number of individual characteristics (Table 3). Two data points appeared to be outliers based on Cook's D-statistic and were omitted from the data set. With the remaining data set, a strong negative correlation of T_{re} was observed with $\dot{V}o_{2\,max}$ and body-size related parameters (mass, lean body mass, surface area, volume; $p < .001$) but a strong positive correlation with the A_D /mass ratio. A weaker correlation was present when $\dot{V}o_{2\,max}$ was expressed per kilogram of body mass, and with ACTIV and sex. No correlation was present with fat% or skinfold thickness. These results are presented in Fig. 2.

Once $\dot{V}O_{2\,max}$ or the reciprocal of $\dot{V}O_{2\,max}$ was introduced into the regression (Fig. 2, step 1), the residual variance in T_{re} only correlated significantly with the surface to mass ratio. The best (= highest r^2_{adj}) regression equation included $(\dot{V}O_{2\,max})^{-1}$ and A_D/mass ($r^2_{adj} = 0.73$; Table 4, Eq. 1). After inclusion of these two parameters, none of the others contributed significantly.

Table 3 First order correlations of individual characteristics with physiological variables, as measured at the end of the heat exposure. Correlation coefficients are represented in classes to provide a better understanding of the relationships: + + $p < 0.001$, $r > 0.70$; + $p<0.05$, $0.70>r>0.40$; (+) $p<0.10$, $0.40>r>0.30$; — — $p<0.001$, $r<-0.70$; — $p<0.05$, $-0.70 <r<-0.40$; (—) $p < 0.10$, $-0.40 < r <-0.30$. Sex: negative correlation means: men lower. $\dot{V}O_{2\,max}$ Maximal oxygen uptake, $\dot{V}O_{2\,max}\,kg^{-1}$ maximal oxygen uptake per kilogram of body mass, $\dot{V}O_{2\,max}\,kg^{-1}$ ff maximal oxygen uptake per kilogram of fat free body mass. For other definitions see Tables 1 and 2

	T_{re}	T_{sk}	S	HR	%HR_{max}	Loss of mass	Loss of mass· m^{-2}	MAP	FBF	FVC
$\dot{V}O_{2\,max}$	— —	—	— —	— —	— —	+	ns	ns	ns	ns
$\dot{V}O_{2\,max}^{-1}$	—	—	—	—	—	ns	ns	ns	ns	(+)
$\dot{V}O_{2\,max}$ kg^{-1} ff	—	—	—	—	—	ns	ns	ns	ns	ns
%$\dot{V}O_{2\,max}$	++	++	++	++	++	—	ns	ns	ns	ns
$(\dot{V}O_{2\,max})^{-1}$	++	++	++	++	++	—	ns	ns	ns	ns
ACTIVity level	(—)	ns	(—)	ns	ns	(+)	+	ns	ns	ns
Skinfolds	ns	ns	ns	ns	ns	ns	ns	+	ns	ns
Fat%	ns	+	ns	ns	ns	ns	ns	ns	(—)	—
Mass	— —	—	— —	— —	—	+	ns	ns	ns	ns
Lean body mass	— —	—	— —	— —	— —	+	ns	+	ns	ns
A_D	— —	—	— —	— —	— —	+	ns	+	ns	ns
A_D/mass	++		+	+	+	—	(—)	—	ns	ns
Body volume	— —	—	—	—	—	+	ns	+	ns	ns
Sex	—	—	—	—	—	ns	ns	ns	ns	ns

Table 4 Regression coefficients for various physiological heat stress reactions with individual parameters. For definitions see Tables 1 and 2

equation nr.	independent variable	unit	Intercept	$\dot{V}O_{2\,max}$	$\%\dot{V}O_{2\,max}$	$(\dot{V}O_{2\,max})^{-1}$	activity level	Skinfolds	Fat%	Lean body mass	A_D	A_D/mass	Body mass	r^2_{adj}
1	T_{re}	°C	36.33			2.72						36.37		0.73
2	T_{sk}	°C	37.11	-0.31					0.031					0.59
3	S	$J \cdot g^{-1}$	1.33			12.0								0.76
4	S	$J \cdot g^{-1}$	10.3				-0.17		0.03	-0.09				0.76
5	Sweat loss	g	-518				33.						16.	0.65
6	Sweat loss$\cdot m^{-2}$	g m^{-2}	-31				17.						5.	0.36
7	HR	beat$\cdot min^{-1}$	-2.4		1.99							2610.		0.71
8	HR	beat$\cdot min^{-1}$	199.2	-18.8										0.63
9	HR	beat$\cdot min^{-1}$	137.3			146.1					-26.5			0.68
10	$\%HR_{max}$	%	68.6		0.92						-14.7			0.68
11	$\%HR_{max}$	%	38.3			98.8								0.64
12	MAP	mm Hg	127.8						0.33			-1984		0.34
13	MAP	mm Hg	58.4				1.92	0.335						0.37

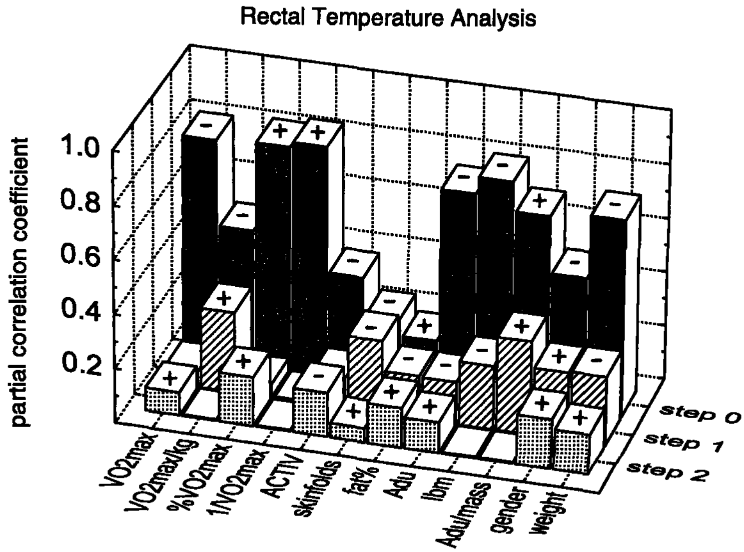

Fig. 2 Partial correlation coefficients of individual characteristics with rectal temperature as measured at the end of the heat exposure. Coefficients are presented for three stages of the regression analysis: step 0, first order correlation; step 1, correlation after adjustment of data for $(\dot{V}o_{2\,max})^{-1}$; step 2, correlation after additional adjustment of data with A_D /mass ratio. For definitions see Tables 1 and 2

Skin temperature

Skin temperature at the end of the exposure correlated well with $\dot{V}o_{2\,max}$ (expressed in different units/definitions: absolute: r = -0.67; per kilogram: r = -0.59; inverse: r = 0.70; percentage of maximum: r = 0.73), with adiposity (fat% r = 0.55), anthropometry [body surface area (A_D), r = -0.57; body mass r = -0.46], and sex (r = -0.50, men higher T_{sk}). No significant correlation was present with skinfold thickness, activity level and A_D /mass ratio. The best complete equation was formed when two parameters were entered: fat% and $\dot{V}o_{2\,max}$ r^2_{adj} = 0.59; Table 4, Eq. 2). Alternative equations with a slightly lower amount of the variance explained included, instead of $\dot{V}o_{2\,max}$, %$\dot{V}o_{2\,max}$, $(\dot{V}o_{2\,max})^{-1}$ all combined with fat%. After inclusion of $\dot{V}o_{2\,max}$, sex effects became insignificant.

Body heat storage

The S (in joules per gram) was strongly correlated with $\dot{V}o_{2\,max}$ [absolute (r = -0.85), percentage of maximum (r = 0.88), inverse of $\dot{V}o_{2\,max}$ (r = 0.88)], anthropometry (body surface area (r = -0.76), mass (r = -0.71)), A_D /mass (r = +0.65) and to a lesser degree with sex (r = -0.53, men lower S) and activity level (r = -0.37). Skinfolds and fat% were not significantly correlated to S.

Once $\dot{V}o_{2\,max}$ in one of its forms was entered, none of the other parameters improved the prediction. The best equations include $(\dot{V}O_{2\,max})^{-1}$ or ACTIV and lean body mass (LBM) (r^2_{adj} = 0.76, Table 4, Eqs. 3,4).

Sweat loss

Correlation of sweat loss was significant with aerobic power expressed as $\dot{V}O_{2\,max}$ (r = 0.62), $(\dot{V}O_{2\,max})^{-1}$ (r = -0.57),%$\dot{V}O_{2\,max}$ (r = -0.49), and with anthropometric data (BSA r = 0.78; LBM r = 0.71; A_D/mass r = -0.65; mass r = 0.76). No significant relationship was present with adiposity and sex. The best equation included ACTIV with either A_D or mass (r^2_{adj} = 0.60, Table 4, Eq. 5).

With sweat loss expressed per metre squared of A_D, $\dot{V}O_{2\,max}$ (r = 0.46), $(\dot{V}O_{2\,max})^{-1}$ (r = -0.44), A_D (r = 0.61), LBM (r = 0.54), A_D/mass ratio (r = -0.52) and mass (r = 0.60) showed significant correlations. In this case the best equation included ACTIV and body mass (r^2_{adj} = 0.36; Table 4, Eq. 6). In this case, mass could be replaced with A_D, or A_D/mass, with a slight reduction in r2.

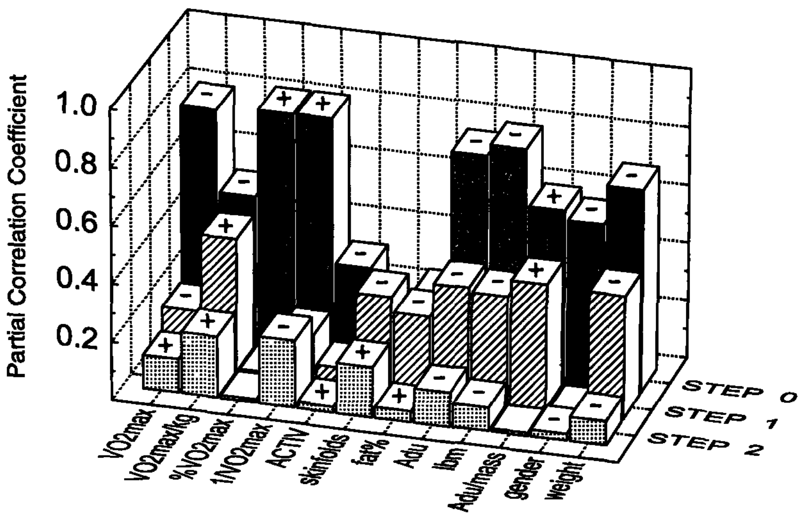

Fig. 3 Partial correlation coefficients of individual characteristics with heart rate as measured at the end of the heat exposure. Coefficients are presented for three stages of the regression analysis: step 0. first order correlation; step 1, correlation after adjustment of data for %$\dot{V}O_{2\,max}$; step 2, correlation after additional adjustment of data with A_D/mass ratio. For definitions see Tables 1 and 2

Heart rate

The final values for HR correlated well with measures of aerobic power ($\dot{V}O_{2\,max}$ r = -0.79; %$\dot{V}O_{2\,max}$ r = 0.79; $(\dot{V}O_{2\,max})^{-1}$ r = 0.79), anthropometry (mass, r = -0.71; LBM, r =

-0.78; A_D, r = -0.75; A_D/mass, r = 0.62) and sex (r = -0.48). The relations with ACTIV and adiposity were not significant. One subject was eliminated as an outlier, based on the Studentized residual. With many parameters having a comparable correlation, several equations for HR were obtained. The result of the following analysis is presented in Fig. 3, where %$\dot{V}O_{2\,max}$ is entered into the equation first in step 1 and A_D /mass in step 2, resulting in an equation with an r^2_{adj} of 0.71 (Table 4, Eq. 7). Substitution of A_D /mass with other anthropometric measures produced a comparable level of variance explained. Using other parameters for aerobic power resulted in equations with only $\dot{V}O_{2\,max}$ (r^2_{adj} = 0.63) or with $(\dot{V}O_{2\,max})^{-1}$ and A_D (r^2_{adj} = 0.68; Table 4, Eqs. 8,9).

When HR was expressed relative to the individual's maximal HR, the best equations had a similar form, and similar amounts of variance explained to those for HR (Table 4, Eqs. 10,11). In this case, A_D was the only parameter which contributed after %$\dot{V}O_{2\,max}$ was entered in the equation. The other anthropometric data were insignificant in that phase. Sex lost its effect on both HR and maximal percentage heart rate (%HR_{max}) once aerobic power in any form was entered into the equation.

Forearm blood flow
The FBF hardly showed any relationship with individual parameters. The correlations with fat% were almost significant (r = -0.33).

Mean arterial blood pressure
The MAP was not directly correlated with $\dot{V}O_{2\,max}$, activity level and sex (Table 3), but showed a relationship with adiposity (skinfolds r = 0.54), A_D (r = 0.40), A_D /mass (r = -0.58) and mass (r = 0.51). The best total equations included either fat% and A_D/mass (r^2_{adj} = 0.34) or ACTIV and skinfold thickness (r^2_{adj} = 0.37).

Forearm vascular conductance
The FVC was related to adiposity (fat% r = -0.42) and (weakly) to $\dot{V}O_{2\,max}$; the latter only when expressed per kilogram of body mass (r = 0.33). As the total explained variance did not go above 18%, no equations are presented.

3.4 Discussion

3.4.1 Methodology

Fixed versus relative workload

In the present study the subjects exercised at a fixed intensity which differs from most other studies where relative loads (equal percentage of $\dot{V}O_{2\,max}$) have been used (Havenith and van Middendorp 1990; Pandolf et al., 1988). This choice was made as the aim of the study was to determine relative influences of different individual parameters. If a relative work load were to have been chosen, according to Åstrand (1960) and Saltin and Hermansen (1966), the reactions of body core temperature for all subjects should have been equal for all subjects, or at least independent of their $\dot{V}O_{2\,max}$. Thus it would not be possible to weigh the importance of $\dot{V}O_{2\,max}$ in relation to other individual characteristics for the subjects' heat stress response.

Sex

Women were included among the subjects with the idea that sex differences in thermoregulation during exercise could be attributed to personal characteristics other than sex. This assumption was based on studies where sex effects were absent due to matching of groups of men and women for their body size and $\dot{V}O_{2\,max}$ (Avellini and Kamon 1980; Frye and Kamon 1981; Frye et al., 1982), or where the sex effect in unmatched groups could be fully explained by differences in $\dot{V}O_{2\,max}$, body fat content and A_D (Havenith and van Middendorp 1990). The correctness of this assumption was confirmed by the data from this experiment: once data were adjusted for $\dot{V}O_{2\,max}$ differences, all sex differences in the results disappeared. Thus, the addition of women to the group of subjects was only relevant to cover a wider span in some of the individual characteristics such as body fat% and $\dot{V}O_{2\,max}$.

3.4.2 Relative importance of parameters

The relative contributions of parameters can be evaluated from their regression coefficients. However, as variance and units differ for each parameter and dependent variable, estimation of the effect of a parameter on a dependent variable is difficult when only looking at the regression coefficient. A different way of presenting relative influences has been presented by Havenith and van Middendorp (1990), who used the standardized regression coefficients to express the relative contributions of individual parameters to the individuals' heat strain. The value of the standardized regression coefficient is the change in the dependent variable (e.g. T_{re}, HR) expressed in units of its standard deviation, when the independent parameter changes by 1 standard deviation. With this method, the afore-mentioned problems with ranges and units are solved. Using the standardized regression coefficients, the relative contribution of the different parameters to the explained variance was calculated as (see also chapter 1):

$$\textit{contribution to } r^2 = \frac{|\textit{standardized regression coefficient for parameter}|}{\sum |\textit{all standardized regression coefficients in equation}|} \cdot r^2$$

The results of this calculation are presented in the pie-charts of Fig. 4, separating unexplained variance in the data from the relative contributions by the different parameters. The separate pie charts in Fig. 4 relate to the equations in Table 4.

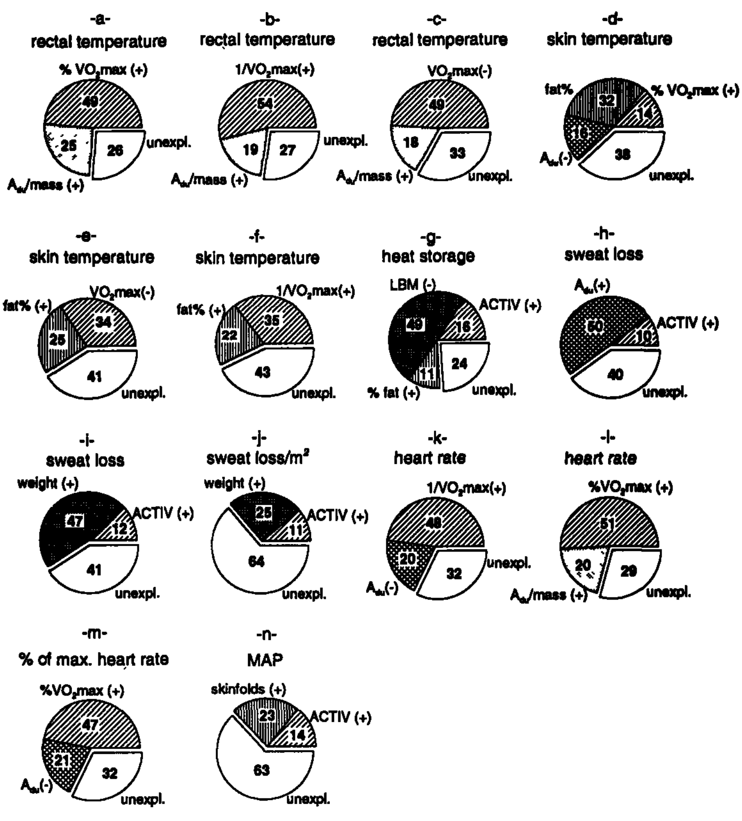

Fig. 4 Sensitivity of physiological variables as measured at the end of the heat exposure for influences of parameters describing interindividual differences. Each pie segment represents the relative influence of a certain parameter on the total variance explained with the number in the segment representing its size as a percentage. Unexpl. = Amount of unexplained variance. LBM = Lean body mass, other definitions see Tables 1 and 2

3.4.3 Heat strain

When we look at the relative contribution of the individual differences to the responses of T_{re}, T_{sk}, and S, it would appear that parameters related to aerobic power ($\dot{V}O_{2\,max}$, $(\dot{V}O_{2\,max})^{-1}$, $\%\dot{V}O_{2\,max}$) make the major contributions to the variance.

Rectal temperature

For T_{re}, $\dot{V}O_{2\,max}$ in the three forms presented (Fig. 4 a,b,c) explained roughly 50% of the variance. Body size related parameters and more specific A_D/mass, contributed 18%-25%, which is less than half of the $\dot{V}O_{2\,max}$ contribution. These results thus were only partially in accordance with the commonly accepted statement that T_{re} increases relative to the exercise intensity expressed as a percentage of $\dot{V}O_{2\,max}$(Åstrand 1960; Saltin and Hermansen 1966). It was observed that a lot of variance in T_{re} remained, not attributable to this parameter. Part of this variance was explained by the subjects' A_D/mass relationship with big subjects (= high A_D, low A_D/mass) having a lower T_{re} (even after correction of T_{re} data for differences in aerobic power). The latter can be explained by the higher A_D for heat loss of big subjects and their higher heat storage capacity, while the heat load was equal for all subjects. In an earlier experiment, Havenith and van Middendorp (1990), using loads relative to the individual's $\dot{V}O_{2\,max}$, have found the same positive correlation between A_D/mass ratio (and a negative with A_D) and core temperature not only for a warm-humid, but also for a neutral and a hot-dry climate. The positive correlation was highest in the warm-humid climate, however, implying that big subjects have the most marked advantage in the warm-humid climate, whether their exercise intensity is fixed or relative to their $\dot{V}O_{2\,max}$. The literature which has suggested an advantage of a high A_D/mass for heat stress response (Havenith 1985), is thus contrary to the present observations. In studies where this advantage has been observed, possibly A_D/mass and fat% interact, e.g. when people with the same mass have different A_D/mass ratios due to different fat contents (men compared to women, Shapiro et al., 1980).

Skin temperature

For T_{sk}, more variance remained unexplained (41%) (Fig. 4 d,e,f). The main parameter was once more $\dot{V}O_{2\,max}$ (34% contribution). An additional parameter which contributed about 24% was fat%. Part of the effect of aerobic power could also be explained by A_D, which gave contributions for $\%\dot{V}O_{2\,max}$ (14%), A_D (16%) and fat% (32%) (Fig. 4d). Thus, in other words, T_{sk} was lower with increasing aerobic power, higher with increasing adiposity and lower with increasing A_D. These parameters most likely acted through the sweating system: high aerobic power implying partial acclimation (Havenith 1985; Kenney and Havenith 1993) and thus improved sweating and skin cooling. It has been found that the effect of high fat% may not be due to the insulating effect of body fat as this layer is well transfused with blood and thus does not form a heat resistance in heat exposures (Burse 1979). Also if fat were to influence T_{sk} through its insulative effect, a significant effect of skinfold thickness (the actual thickness of insulation) would be expected. This was not observed. It is thought that it is more likely to represent also a relationship with general fitness and thus with partial heat acclimation (Pandolf et al., 1988). The A_D, having a negative effect on T_{sk} represented the heat loss capacity of the body.

Heat Storage

The findings for the effects of individual parameters on S were similar to those of T_{re} and T_{sk} combined. Again aerobic power was an important factor (Table 3, Eq. 3). Another combination of parameters which gave a good prediction was formed by LBM, fat% and regular activity level (Fig. 4 g). The similar importance of both aerobic power and LBM in the separate equations could be attributed to their mutual relationship. Subjects with a high LBM had a higher muscle mass and thus on average a higher $\dot{V}O_{2\,max}$ than subjects with a low LBM. Thus with the fixed exercise intensity used, LBM and $\%\dot{V}O_{2\,max}$ were correlated.

The effect of adiposity was smaller than would have been expected when looking at studies from Burse (1979), Buskirk (1971) and Haymes et al., (1975) who have found a clear adverse effect of adiposity. However, the subjects in their studies were not matched for aerobic power, which meant that the fatter subjects in general were less fit. In the present study, though the subjects were not matched, the variance due to aerobic power was taken into consideration, thus resulting in a better separation of the effect of adiposity from the aerobic power effect. The effect of adiposity remained significant however, with fatter subjects having a higher increase in body heat content.

3.4.4 Heat loss

Sweat loss

For evaporative heat loss, though very limited in this climate, the subjects' loss of mass over the session could be regarded as an effector response. In general it has been stated that loss of mass (i.e. sweat rate) is related to absolute heat production or absolute exercise intensity (Drinkwater and Horvath 1979). In the present experiment, though the exercise intensity was equal for all subjects, loss of mass was not equal for all of them at all (range 397-1403 g). Total loss of body mass was found to be positively related to body size (A_D or mass), $\dot{V}O_{2\,max}$ and regular activity level (Table 3; Fig. 4 h,i). With loss of mass expressed per unit of A_D, the amount of variance explained was reduced (Fig. 4j). This was due to the (partial) correction for body size. The parameters in the prediction are the same however, with ACTIV maintaining a similar contribution and a reduced but still significant contribution of body size. The fact that the regular activity level played an important role, as did $\dot{V}O_{2\,max}$(Table 3), reflected the effect of training on the individual's acclimation status. The latter was improved by training and thereby sweating response improved too (Henane et al., 1977; Avellini et al., 1982). The difference between ACTIV and $\dot{V}O_{2\,max}$, in its effect on sweat loss as has been shown, may reflect the difference between achieved fitness and genetic fitness (Slattery and Jacobs 1987; Sobolski et al., 1988).

The overall conclusion concerning sweating was that big, fit subjects sweated more than the lean and/or unfit subjects and that they did this at a lower core temperature.

3.4.5 Circulatory responses

Heart rate

In the equations for HR, aerobic power expressed as $(\dot{V}O_{2\,max})^{-1}$ or $\%\dot{V}O_{2\,max}$ explained 50% of the variance (Fig. 4 k,l,m). The A_D or A_D/mass, took care of the other 20%. For HR expressed as percentage of the individual's maximum, results were almost identical. This reflected the finding that the individual's HRmax was not related to the parameters used in the equation. Thus HR and %HRmax have equal information content in the present subject group. This was found to be different in a previous study by Havenith et al., (1993, 1995). There, however, a large variation in age was included in the group. Then, the resulting effect of age on HRmax resulted in a discrepancy between the effects of individual parameters on HR and on %HRmax.

The effect of $\dot{V}O_{2\,max}$ on HR contained two underlying effects: firstly, as the exercise intensity was fixed, the value for $\dot{V}O_{2\,max}$ determined the relative load of the subjects. A high $\dot{V}O_{2\,max}$ implied a high stroke volume and also a low relative load and therefore a small increase in HR to provide the muscles with oxygen. This would have been the major part of the $\dot{V}O_{2\,max}$ contribution. Secondly, $\dot{V}O_{2\,max}$ affected the change in HR which was due to the additional external heat load. As mentioned before, fitter subjects in general have more efficient sweating systems. Through this, they also have more efficient skin cooling and thus increase the efficiency of heat removal from core to skin by the skin blood flow. Thus the increase in HR needed is smaller. The effect of A_D on HR has been shown to work in a similar manner: a higher A_D provides more heat loss surface, resulting in improved cooling and thus more efficient heat removal from core to skin (McArdle et al., 1984).

FBF, MAP, FVC

The amount of variance explained for FBF, MAP and FVC was quite low (< 36%), which is similar to observations in other experiments (Havenith and van Middendorp 1990). The general finding for these variables was that adiposity had a negative effect on FBF and FVC and a positive effect on MAP (Fig. 4 n). The relationship between FBF and adiposity has previously been investigated by Vroman et al., (1983), who have found a similar negative relationship. The two groups they have compared were not identical with respect to their $\dot{V}O_{2\,max}$ however, whether expressed per kilogram of total body mass or of fat free body mass. In the present data, MAP was related to body size (A_D, mass, A_D /mass). Thus, the bigger and fatter the subject, the lower the FVC and the higher the MAP. The $\dot{V}O_{2\,max}$ did not have a significant effect, but activity level had a secondary effect on MAP. The more active the subject, the higher the MAP. Considering the levels of MAP reached at the end of the exposure (mean 80 mmHg), this could be interpreted as the ability of active subjects to prevent diastolic blood pressure from falling too low.

3.4.6 Skinfolds versus fat%

In the present study adiposity was defined as total body fat% as determined by under water weighing and as the thickness of four skinfolds. This separation was made to test whether sub-cutaneous fat (skinfolds) affects thermoregulation through its insulative properties or whether thermoregulation is affected more by total body fat as a passive body mass with a lower than average specific heat. Table 3 shows that skinfold thickness only affected MAP as a first order effect, whereas, fat% affected T_{sk} and FVC. Thus, there was no evidence that the thickness of the subcutaneous fat layer affected heat loss because in that case the relationship of skinfold thickness with T_{sk} would have been stronger than that of fat%.

3.4.7 Non-linear effects of $\dot{V}O_{2\,max}$

With %$\dot{V}O_{2\,max}$ in general being a good predictor for body temperature, the question was posed whether this was really due to the information given by the relative exercise intensity, or whether this may have been due in part to the non-linear presentation of maximal aerobic capacity in that case. In the first case, % $\dot{V}O_{2\,max}$ should have been a better predictor than $(\dot{V}O_{2\,max})^{-1}$, in the second this should have been the reverse or similar. It was found that in most cases $(\dot{V}O_{2\,max})^{-1}$ was an even better predictor than $\dot{V}O_{2\,max}$ or %$\dot{V}O_{2\,max}$ for the present data with the fixed exercise intensity. This further would seem to suggest that the effect of improvements in aerobic power on heat strain is strongest when $\dot{V}O_{2\,max}$ is low, and that the reductions in heat strain get smaller as $\dot{V}O_{2\,max}$ becomes higher.

In summary, the technique of stepwise multiple regression was used to determine the relative importance of a number of individual characteristics for human responses to heat stress. The major conclusion was that for the conditions used (equal exercise intensity, warm humid climate) the subjects' aerobic power was the major contributor. Body size related parameters contributed also, be it with about half the effect of $\dot{V}O_{2\,max}$ The subjects with a high A_D for cooling showed the lowest heat strain. The widely accepted concept that body core temperature is determined almost completely by exercise intensity expressed as $\%\dot{V}O_{2\,max}$ and sweat loss by absolute exercise intensity, was only supported in part by the results for comparisons among subjects. For both variables, other individual characteristics were also shown to contribute substantially.

References

Akers RF, Buskirk ER (1969) *An underwater weighing system utilizing "force cube" transducers.* J Appl Physiol 26:649-652

Anderson RK, Kenney WL (1987) *Effect of age on heat-activated sweat gland density and flow during exercise in dry heat.* J Appl Physiol 63:1089-1094

Åstrand I (1960) *Aerobic work capacity in men and women with special reference to age.* Acta Physiol Scand 49 [Suppl 169:1-92

Avellini BA, Kamon E (1980) *Physiological responses of physically fit men and women to acclimatization to humid heat.* J Appl Physiol 49:254-261

Avellini BA, Shapiro Y, Fortney SM, Wenger CB, Pandolf KB (1982) *Effects on heat tolerance of physical training in water and on land.* J Appl Physiol 53:1291-1298

Burse RL (1979) *Sex differences in human thermoregulatory response to heat and cold stress.* Hum. Factors 21:687-699

Buskirk ER (1971) *The physiological basis of rehabilitation.* Saunders, Philadelphia

Drinkwater BL, Horvath SM (1979) *Heat tolerance and aging.* Med Sci Sports 11:49-55

DuBois D, DuBois EF (1916) *Clinical calorimetry: a formula to estimate the appropriate surface area if height and weight be known.* Arch Int Med 17:863-871

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

Frye AJ, Kamon E (1981) *Responses to dry heat of men and women with similar aerobic capacities.* J Appl Physiol 50:65 70

Frye AJ, Kamon E, Webb M (1982) *Responses of menstrual women, amenorrheal women and men to exercise in a hot, dry environment.* Eur J Appl Physiol 48:279-288

Gagge AP (1973) *Rational temperature indices of man's thermal environment and their use with a 2-node model of his temperature regulation.* Fed Proc 32:1572-1582

Givoni B, Goldman RF (1973) *Predicting effects of heat acclimatization on heart rate and rectal temperature.* J Appl Physiol 35:875-879

Havenith G (1985) *Individual parameters in thermoregulatory control; a review.* Institute for Perception, Soesterberg, NL Report no. IZF 1985-26

Havenith G, van Middendorp H (1990) *The relative influence of physical fitness, acclimation state, anthropometric measures and gender on individual reactions to heat stress.* Eur J Appl Physiol 61:419-427

Havenith G, Inoue Y, Luttikholt VGM, Kenney WL (1993) *Combined effect of age and $\dot{V}o_{2\,max}$ on body temperature during work in a warm, humid climate in a heterogeneous subject population.* Proceedings of Thermal Physiology Symposium, IUPS, Glasgow

Havenith G, Inoue Y, Luttikholt VGM, Kenney WL (1995) *Age predicts cardiovascular, but not thermoregulatory, responses to humid heat stress.* Eur J Appl Physiol 70:88-96

Haymes E, McCormick R, Buskirk E (1975) *Heat tolerance of exercising lean and obese prepubertal boys.* J Appl Physiol 39:457-461

Henane R, Flandrois R, Charbonnier JP (1977) *Increases in sweating sensitivity by endurance conditioning in man.* J Appl Physiol 43:822-828

ISO (1982) *Hot environments, heat stress estimation for working humans based on WBGT.* International Standard Organization, Geneva, Report no. 7243

ISO (1989) *Hot environments, analytical determination and interpretation of thermal stress using calculation of required sweat rate.* International Standard Organization, Geneva, Report no. 7933

Kenney WL (1985) *A review of comparative responses of men and women to heat stress.* Environ Res 37:1-11

Kenney WL (1988) *Control of heat-induced vasodilation in relation to age.* Eur J Appl Physiol 57:120-125

Kenney WL, Havenith G (1993) *Heat stress and age: skin blood flow and body temperature.* J Therm Biol 18:341-344

Lotens WA (1993) *Heat transfer from humans wearing clothing.* Thesis, Technical University, Delft

McArdle WD, Magel JR, Gergley TG, Spina RJ, Toner MM (1984) *Thermal adjustment to cold water in resting men and women.* J Appl Physiol 56:1565-1571

Pandolf KB, Cadarette BS, Sawka MN, Young AJ, Francesconi RP, Gonzalez RR (1988) *Thermoregulatory responses of middle-aged and young men during dry-heat acclimation.* J Appl Physiol 65:65-71

Ross AM, Jackson AS (1990) *Exercise concepts, calculations and computer applications* Benchmark Press, Carmel

Saltin B, Hermansen L (1966) *Esophageal, rectal and muscle temperature during exercise.* J Appl Physiol 21:1757-1762

Shapiro Y, Pandolf KB, Avellini BA, Pimental NA, Goldman RF (1980) *Physiological responses of men and women to humid and dry heat.* J Appl Physiol 49:1-8

Slattery ML, Jacobs DR (1987) *The inter-relationships of physical activity, physical fitness, and body measurements.* Med Sci Sports Exerc 19:564-569

Sobolski JC, Kolesar JJ, Kornitzer MD, De Backer GG, Mikes Z, Dramaix MM, Degre SG, Denolin HF (1988) *Physical fitness does not reflect activity patterns in middle-aged workers,* Med Sci Sports Exerc 20:6-13

Vroman NB, Buskirk ER, Hodgson JL (1983) *Cardiac output and skin blood flow in lean and obese individuals during exercise in the heat.* J Appl Physiol 55:69-74

Wenzel HG, Mehnert C, Schwarzemau P (1989) *Evaluation of tolerance limits for humans under heat stress and the problems involved.* Scand J Work Environ Health [Suppl. 1] 15:7-14

Whitney RJ (1953) *The measurement of volume changes in human limbs.* J Physiol (Lond) 121:1-27

Wilkinson L (1990) *SYSTAT: the system for statistics.* Systat, Evanston, Il

4

The influence of individual characteristics on physiological response during relative load exercise in different climates

Chapter 4

The influence of individual characteristics on physiological response during relative load exercise in different climates

George Havenith · Henk van Middendorp

Adapted from:
European Journal of Applied Physiology, 61:419-427, 1990

Summary. An experiment was set up to determine the effect of individual characteristics on the response to relative work loads over several climates. The studied individual characteristics were gender, $\dot{V}O_{2\,max}$, body mass, body *surface area* (A_D), body fat percentage (%fat) and daily activity level (ACTIV). For this purpose, 12 male and 12 female subjects were exposed to a neutral [ambient temperature (T_a) 21°C, relative humidity (r.h.) 50%)], a warm, humid (T_a 35°C, r.h. 80%) and a hot, dry (T_a 45°C, r.h. 20%) climate. The tests consisted of three subsequent 30 min. periods, starting with rest and followed by two exercise intensities (25%, and 45% maximal O_2 intake ($\dot{V}O_{2\,max}$)). Subjects were seated seminude in a net chair behind a cycle ergometer. Their physiological responses were recorded and the data obtained at the end of the exposure were statistically analysed. The mean responses for rectal temperature (T_{re}), body heat storage (Store) and heart rate (HR), as determined at the end of the 45% load phase, were submitted to a multiple regression analysis. Mass and ACTIV were shown to contribute to the variance in the responses of T_{re} and Store. As an interaction between climate type and individual characteristics may exist, the impact of individual characteristics on the physiological responses may be different for the different climates. This was studied by an analyses of the differences in responses between climates. This analyses revealed significant effects of individual characteristics on the differences in responses between climates. $\dot{V}O_{2\,max}$, %fat and ACTIV had significant effects in several comparisons. Gender showed a trend of an effect ($0.07 < p < 0.10$). Thereby a significant interaction between climate and individual characteristics was demonstrated. This interaction will be studied in more detail in Chapter 5.
In the multiple regression analyses of these "difference" data, $\dot{V}O_{2\,max}$, %fat, ACTIV, and body mass were found to be relevant parameters. Gender lost its influence once data were corrected for $\dot{V}O_{2\,max}$ or %fat.

Key words: Heat strain - Heat stress - Individual response - Work- Climate

4.1 Introduction

A problem in the prediction of heat stress/strain has always been the large inter-individual variability in the heat stress response. Models for heat stress/strain predictions (Stolwijk 1971; Gagge 1973; Givoni and Goldman 1973a, b; ISO 1982, 1988) are therefore limited to prediction of the average population response, which may involve risks for individuals at the extremes of population distribution (Wenzel et al., 1989). Several reviews (Havenith 1985; Kenney 1985) have summarized the parameters which are relevant to these individual differences, e.g. physical fitness, acclimatization, hydration state, drug and alcohol use, hypertension, gender, anthropometric data and age. Several of these parameters have been studied but usually only one at a time. Some studies matched subjects for one parameter, while investigating another (Frye and Kamon 1981). The present study has aimed at the simultaneous study of several parameters (fitness, acclimatization status, gender and anthropometric data), to determine their influences on the heat stress response of an individual subject. The variables which are most interesting in relation to heat strain prediction are body heat storage (STORE), heart rate (HR) and body core temperature (rectal, T_{re}), as their values are often used in setting limits for heat exposure (ISO 1982, 1988).

In this chapter two main questions will be dealt with. The first is, notwithstanding possible interactions between climate and individual characteristics, what individual parameters determine who has the lowest core temperature, heat storage and heart rate averaged over a cool, a warm humid and a hot dry climate. Considering the data presented in chapter 1 (section 1.2.1), an interaction between climate and individual parameters is expected for their effect on physiological responses. The second question therefore is whether in comparing the physiological responses to exercise in different climates, there is a statistically significant interaction of the individual characteristics with these responses.

4.2 Methods

Subjects.

Twenty-four subjects were selected for the test, 12 males and 12 females. They were informed of the test procedures and risks, after which they gave signed informed consent. The groups of males and females were balanced regarding their fitness, expressed in maximal oxygen uptake ($\dot{V}o_{2\,max}$, ml·min^{-1}·kg fatfree body mass $^{-1}$: group averages, males 55.4 ml·min^{-1}·kg $^{-1}$, females 53.5 ml·min^{-1}·kg^{-1} Their fitness was determined by extrapolation of the results of an incremental exercise test at sub-maximal levels of intensity (Åstrand and Rodahl 1986). Body surface area (A_D) was determined by standard methods (DuBois and DuBois 1916) and percentage of body fat was determined by measuring the skinfold thicknesses (Durnin and Womersley 1974).

Experimental protocol

This included three tests on each subject: a control test in a cool environment (CO: T_a 21°C, r.h. 50% and two heat stress tests in climates with similar cooling power (wet bulb globe temperature, WBGT). One heat stress test was performed in a warm humid climate (WH: T_a 35°C, r.h. 80%, WBGT 31.9°C), the other in a hot dry climate (HD: T_a 45°C, r.h. 20%, WBGT 31.4°C). The tests were performed on separate days, with 1 or 2 days in between, to avoid changes in acclimatization status. The order of the tests was balanced over the subjects to avoid sequence effects. Each of the three tests was identical except for the climate. The subjects were dressed in shoes, shorts and in addition the females wore bras. During the test the subject was seated in a wire chair behind an electronically controlled cycle ergometer (modified Monark, Monark-Crescent AB, Varburg, Sweden) in a reclining position. The test was split up into three periods of 30 min each. In the first period the subjects rested in the chair, in the second they cycled with an exercise intensity chosen to demand an oxygen uptake of 25%$\dot{V}O_{2\,max}$ (warm-up fase) and in the third, final load, period they worked at 45%$\dot{V}O_{2\,max}$.

Oxygen uptake was measured with a custom built closed circuit oxygen system, using a polarographic oxygen analyser (Servomex). The ECG was monitored continuously, from which HR was deduced and recorded. Body core temperatures were recorded by a rectal probe, inserted to 12 cm beyond the anal sphincter (YSI700 linear thermistor) and by a thermocouple, inserted in the oesophagus to the level of the right atrium (about 37-40 cm from the nose).

Average skin temperature (T_{sk}) was calculated from seven separate measurements, weighted for the surface area they represented:

$$T_{sk} = 0.07\,(T_{head} + T_{upperarm}) + 0.175\,(T_{chest} + T_{back}) +$$
$$0.12\,T_{lowerarm} + 0.19\,T_{upperleg} + 0.20\,T_{lowerleg} \qquad (°C)$$

Heat storage (STORE) was calculated by a weighted sum of T_{re} and T_{sk} deviations from fixed values of 37° and 33°C, respectively:

$$STORE = 3.48\,[0.8\,(T_{re} - 37) + 0.2\,(T_{sk} - 33)] \qquad (J{\cdot}g^{-1})$$

where 3.48 = heat capacity of body tissue ($J{\cdot}g^{-1}{\cdot}°C^{-1}$).

Systolic, diastolic and mean blood pressure were monitored using a finger cuff connected to a "Fin.A.Press", a continuous plethysmographic blood pressure registration technique (Settels and Wesseling 1985). The finger on which the pressure was measured was kept at the heart level.

The whole set up was mounted on a scale, which determined changes in mass of the cycling subject with an accuracy of 10 g. Sweat dripping off the subject was collected in a basin filled with paraffin oil, from which it could not evaporate, mounted on the scale underneath the subject. All changes in body mass except the metabolic components, could therefore be attributed to sweat actually evaporated from the subject. The subjects replenished all fluid losses during the experiment with water at T_a to avoid dehydration effects. The effect of the body temperature-water temperature difference on body heat storage was negligible. All measurements of body mass were corrected for the water uptake.

The subjects' habitual physical activity was recorded using a questionnaire, describing their participation in exercise programmes, etc. (Ross and Jackson 1990). Activity level (ACTIV) was scored on a 7-point scale, ranging from "avoid walking or exertion" to "run over 10 miles each week or exercise over 3 h each week". Gender was coded as 0 for males and 1 for females.

Statistical analysis.

All data, except the blood flow measurements were averaged over 1 min and recorded by a PDP-11/03 and 11/ 23 computer system. For the analysis the values at the end of the total exposure (end of 45% load) were used, as these usually approached steady-state values. For the study of the relative influence of the individual parameters the technique of regression analysis was used. The statistical analysis was done using the statistical software package "SYSTAT".

Distributions of data were tested for normality using probability plots and skewness and kurtosis calculations. The multiple regression analysis with individual characteristics as independent parameters was performed on the average responses for each person over all climates. This should answer which characteristics determine who has the lowest or highest response (T_{re}, HR and Store) over all climates tested, without considering possible interactions.

Table 1 Ranges of the variables as observed at the end of the 45% load phase.

	Abbreviation	Minimum	Maximum	Mean	SD
age		19	27	23	2.4
body mass (kg)		54.95	85.87	70.6	8.0
Height (m)		1.59	1.93	1.78	0.09
Body surface area (m^2)	A_D	1.56	2.12	1.88	0.14
body fat (%)	%fat	12.6	36.6	23.0	7.5
maximal oxygen uptake ($l \cdot min^{-1}$)	$\dot{V}O_{2\,max}$	2.05	4.05	2.96	0.56
maximal oxygen uptake per kg fatfree body weight ($ml \cdot min^{-1} \cdot kg^{-1}$ fatfree)	$\dot{V}O_{2\,max}$ ff	41.21	64.46	54.4	6.1
sweating setpoint (°C)	setpoint	36.61	38.48	37.6	0.5
sweating gain ($g \cdot h^{-1} \cdot °C^{-1}$)	gain	234	1199	583	266
rectal temperature (°C)	T_{re}	36.9	38.8	38.0	0.4
oesophageal temperature (°C)	T_{oes}	37.2	39.7	38.0	0.5
average skin temperature (°C)	T_{sk}	27.5	39.2	34.3	3.7
body heat storage ($J \cdot g^{-1}$)	Store	-2.9	9.1	2.6	3.1
heart rate (min^{-1})	HR	95	161	134	16
oxygen uptake ($l \cdot min^{-1}$)	$\dot{V}O_2$	0.750	1.800	1.33	0.27
metabolic rate (kW)	Metab	0.258	0.612	0.46	0.09
systolic blood pressure (mm HG)	Syst	74	240	130	28
diastolic blood pressure (mm HG)	Diast	39	124	63	16
mean blood pressure (mm HG)	MAP	53	157	83	18
forearm blood flow ($ml \cdot 100ml^{-1} \cdot min^{-1}$)	FBF	0.8	33.0	10.3	7.2
sweat rate ($g \cdot hr^{-1}$)	sweat	40	1248	500	267

In order to study the presence of an interaction between individual characteristics and climate, for each of the three responses studied (T_{re}, HR and Store), the differences in response between climates were calculated:

$$Response_{HD-CO} = Response_{HD} - Response_{CO}$$

$$Response_{WH-CO} = Response_{WH} - Response_{CO}$$

$$Response_{HD-WH} = Response_{HD} - Response_{WH}$$

These responses then were analysed in a regression analyses with the response differences as dependent variable, and the individual characteristics (A_D, $\dot{V}O_{2\,max}$,

$\dot{V}O_{2\,max} \cdot kg^{-1}$, %$\dot{V}O_{2\,max}$, gender, mass, %fat, ACTIV) as independent parameters. The analysis was performed in an interactive, stepwise manner. The order in which parameters were entered in the equation was determined by the level of their partial correlations with the residual variance in the data. The residual variance and the partial correlation coefficients were recalculated after the introduction of each new parameter. When the partial correlation coefficients were similar for more than one parameter, the parameter which was easiest to measure was selected first. A significance level of 0.1 for the partial correlation of a parameter with the response was considered as a limit for consideration of its introduction in the equation as showing a tendency of an effect. Actual significance for p-values was defined at the level of 0.05. The r^2 values presented are all adjusted r^2 values.

If individual parameters are shown to contribute significantly to the explanation of the variance in these response differences between climates, the conclusion is that there exists an interaction between climate and individual characteristics. If not, the climatic parameters apparently determine the differences between conditions.

4.3 Results

The observed ranges of the anthropometric and functional data of the subjects, as well as of the measured variables in the experiment are presented in Table 1.

Table 2 Regression coefficients (RC) and constants (with standard error SE) for the analysis of the responses averaged over climates for each subject, and the explained variance (adjusted r^2) and significances. Significance of separate parameters: mass: $p<0.05$; ACTIV: $p<0.1$.

response	constant		mass		ACTIV		r^2	p
	RC	SE	RC	SE	RC	SE		
T_{re}	38.76	0.32	-0.013	0.004	0.024	0.014	0.33	0.01
STORE	5.7	1.2	-0.046	0.018	0.10	0.06	0.30	0.02
HR	-	-	-	-	-	-	-	n.s.

The results of the multiple regression analyses for the reaction of T_{re}, STORE and HR (averaged over climates), are presented in Table 2. For both T_{re} and STORE a significant regression equation was obtained with body mass and regular activity level as relevant individual characteristics. Total explained variance for the two equations ranged around 30 to 33%. For the average of the final HR, no relation with individual parameters was observed.

The partial correlation coefficient results for the analysis of the relation between the differences in responses between climates for T_{re}, STORE and HR on the one hand and individual characteristics on the other, are presented in Table 3. The results clearly show a correlation between the difference in responses between climates and individual characteristics. Mainly $\dot{V}O_{2\,max}$, body fat percentage, and the regular activity level are related to the difference in response between climates. When these relations are studied by multiple regression several equations result, which are presented in Table 4. For T_{re}, in the WH - CO comparison two different equations are presented.

Table 3 Overview of individual parameters which have an impact (based on the Pearson correlation coefficient) on the differences in responses between the three used climate types and individual characteristics. Only responses with a significance level below 0.1 are shown. Significant *r* values are marked by a *.

response	difference between condition	number of cases	relevant individual parameter	*r*	*p*
T_{re}	HD - CO	24	-	-	-
	WH - CO	24	$\dot{V}O_{2\,max}$	0.55*	0.01
			%fat	-0.55*	0.01
			ACTIV	0.44*	0.03
			gender	-0.34	0.10
	HD - WH	24	$\dot{V}O_{2\,max}$	-0.37	0.07
STORE	HD - CO	24	$\dot{V}O_{2\,max}$	-0.43*	0.04
	WH - CO	24	ACTIV	0.40*	0.05
	HD - WH	24	$\dot{V}O_{2\,max}$	-0.48*	0.02
			%fat	0.37	0.08
			ACTIV	-0.37	0.08
HR	HD - CO	24	-	-	-
	WH - CO	24	%fat	-0.47*	0.02
			$\dot{V}O_{2\,max}$	0.36	0.09
			gender	-0.37	0.07
	HD - WH	24	-	-	-

4.4 Discussion

In a previous paper (Havenith and van Middendorp, 1990) the data from this study were analysed by multiple regression analyses, using the individual data points from all three climates as a basis. These data were used to answer the question which

Table 4 Overview of constant and regression coefficients (and their standard error) and adjusted r^2 values for the multiple regression analysis of the effect of individual characteristics on the differences in physiological response between different climates.

	difference between condition	constant		$\dot{V}o_{2\,max}$		%fat		ACTIV		mass		r^2	p
		RC	SE	RC	SE	RC	SE	RC	SE	RC	SE		
T_{re}	HD - CO	-										-	n.s.
	WH - CO	0.39	0.43	0.41	0.09					-0.017	0.007	0.42	0.001
		0.73	0.17			-0.021	0.006	0.05	0.02			0.42	0.001
	HD - WH	-										-	n.s.
STORE	HD - CO	9.6	0.9	-0.71	0.31							0.16	0.04
	WH - CO	4.9	0.4					0.17	0.08			0.14	0.05
	HD - WH	5.7	1.5	-1.28	0.49							0.20	0.02
HR	HD - CO	-										-	n.s.
	WH - CO	35	5			-0.47	0.19					0.19	0.02
	HD - WH	-										-	n.s.

individual parameters contributed to the explanation of heat stress response, after the data were first corrected for the influence of the climate and the work rate. As however the same subjects were used in all three conditions, which would have been the proper approach for the analyses of variance with subject as a parameter, and which is a common approach found in literature, this creates a problem for regression analyses. The data points for each subject, though obtained in different experiments, cannot be regarded as independent. Though this does not affect the correlation values or the r^2 values, nor the regression coefficients as they were presented, and though it has only a minor effect on adjusted r^2 values, the calculation of the significance (p) of equations in that study must be regarded as suspect as the n-value (number of points) for its calculation is incorrect. As there is no correction for this effect available (e.g. similar to the Bonferroni approach in multiple T-tests or correlations), we reanalysed the data using the averages of the responses over the climatic conditions. Thus this analyses, similar to the old one, looks at the relation between individual characteristics and physiological responses over various climates combined. The difference is the lower power due to the reduction of the number of data points to 24.

The results of these analyses (Table 2) show that for T_{re} and STORE individual parameters do play a role. Body mass and daily activity level (ACTIV) both contribute with mass being the major contributor. Earlier work by Åstrand (1960) and Saltin and Hermansen (1966) suggested that the increase in core temperature during work is defined by the relative work rate, i.e. the percentage of the maximal work rate or oxygen consumption. Climate and other personal characteristics should show only a minor influence. As the core temperature is the major contributor to heat storage, similar reasoning should be applicable to the effect of relative work rate on heat storage. However, even though relative work loads were used, for both variables effects of other parameters were observed in the present study. Subjects with a high mass had the lowest core temperatures and heat storages, whereas those with the highest daily activity levels had the highest. For both effects together, the total explained variance is only about one third of the total variance however.

Though the results above provide some information e.g. when one has to select a subject (worker, military) for a task which may have to be performed in a wide variety of climates, one can expect, based on the discussion in section 1.2.1, that there is an interaction between individual characteristics and climate type. Some subjects may perform best of a group in the cold, others in a hot dry climate and again others in a warm humid climate. This interaction was studied using the differences in reaction to the different climates for each subject. The results of the correlation analyses between the differences between conditions on one hand and individual characteristics on the other, are presented in Table 3. If no interaction would be present, no significant correlations should be observed. Thus if no correlation is found, this means that the respective parameter has the same effect in both of the compared climate types. If a correlation is observed, that parameter has a different effect in each of the two compared climate types.

Table 3 clearly shows that significant effects are present, and that these differ depending on which comparison of climatic conditions is made. Observed effects are from $\dot{V}O_{2\,max}$, body fat percentage and daily activity level. The observation of an effect of $\dot{V}O_{2\,max}$ is most surprising, taking into account that relative work loads were used which should have eliminated any effects of the individual's $\dot{V}O_{2\,max}$ (Saltin and Hermansen, 1966).

Having $\dot{V}O_{2\,max}$ and ACTIV both as relevant parameters raises the question whether these are representing the same characteristic. As can be expected, $\dot{V}O_{2\,max}$ and ACTIV are correlated. This correlation is significant (p=0.05), but the correlation coefficient is only 0.4, showing that there is a relation between activity level and $\dot{V}O_{2\,max}$, but leaving room for a, probably genetic, component in $\dot{V}O_{2\,max}$. Thus the effect of ACTIV may be the same as that of $\dot{V}O_{2\,max}$, but it can also have a separate meaning. The ACTIV level gives the number of times the body temperature is raised by exercise, which makes it into a factor representing acclimation level too.

The results of the multiple regression analyses on the differences between conditions are presented in Table 4. Here, combinations of $\dot{V}O_{2\,max}$ with mass or body fat percentage and daily activity level are found as predictors, or single predictors as in Table 3.

As $\dot{V}O_{2\,max}$ is present as a relevant parameter in several of the conditions over all responses, it is interesting to analyse the sign of the correlation for this predictor. Of the effects of $\dot{V}O_{2\,max}$ presented in Table 3 and 4 over all responses together, there is a consistent picture: $\dot{V}O_{2\,max}$ has a positive impact in the WH-CO comparison, but a negative or none in the others (HD-CO and HD-WH). Thus, the increase in response (T_{re}, STORE and HR) to the WH climate compared to both the CO and the HD condition is higher for subjects with a higher $\dot{V}O_{2\,max}$. In other words these comparisons suggest that a high $\dot{V}O_{2\,max}$ is beneficial (lower heat strain) in a CO and a HD climate, but a disadvantage (higher strain) in a WH climate. This point will be addressed in more detail in chapter 5.

4.5 Conclusion

Two conclusions can be drawn from this chapter. The first is that averaged over all climatic conditions, the responses of T_{re} and STORE are, for the relative work load used, related to body mass and daily activity level, of which mass causes the main effect (the higher the mass, the lower the strain). The second is that a significant interaction between climate and individual parameters is present indeed, with $\dot{V}O_{2\,max}$, %fat and ACTIV as parameters of importance. Gender showed a trend of an effect ($0.07 < p < 0.10$). Thus, when analysing the data for each climate separately, a different impact of individual parameters in the different conditions can be expected. This analyses of the separate conditions will be presented in Chapter 5. In the multiple regression analyses of the differences in response between the climates, $\dot{V}O_{2\,max}$, %fat, ACTIV, and body mass were found to be relevant parameters. Gender lost its influence once data were corrected for $\dot{V}O_{2\,max}$ or %fat.

References

Åstrand I (1960) *Aerobic work capacity in men and women with special reference to age.* Acta Physiol Scand 49 [Suppl 169]:192

Åstrand PO, Rodahl K (1986) *Textbook of work physiology.* McGraw-Hill, New York

DuBois D, DuBois EF (1916) *Clinical calorimetry: a formula to estimate the appropriate surface area if height and weight be known.* Arch Intern Med 17:863-871

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

Frye AJ, Kamon E (1981) *Responses to dry heat of men and women with similar aerobic capacities.* J Appl Physiol 50:65-70

Gagge AP (1973) *Rational temperature indices of man's thermal environment and their use with a 2-node model of his temperature regulation.* Fed Proc 32: 1572-1582

Givoni B, Goldman RF (1973a) *Predicting heart rate response to work, environment and clothing.* J Appl Physiol 34:201-204

Givoni B, Goldman RF (1973b) *Predicting effects of heat acclimatization on heart rate and rectal temperature.* J Appl Physiol 35: 875-879

Havenith G (1985) *Individual parameters in thermoregulatory control; a review.* Institute for Perception Report IZF 1985-26. Available from TNO, PO box 23, Soesterberg

Havenith G, van Middendorp H (1990) *The relative influence of physical fitness, acclimation state, anthropometric measures and gender on individual reactions to heat stress.* Eur J Appl Physiol 61:419-427

ISO (1982) *Hot environments. Heat stress estimation for working humans, based on WBGT.* International Standard Organization, Geneva, Report no. 7243

ISO (1988) *Hot environments-analytical determination of thermal stress (required sweat rate).* International Standard Organization, Geneva, Report no. DIS 7933

Kenney LW (1985) *Physiological correlates of heat intolerance.* Sports Med 2:279-286

Ross AM, Jackson AS (1990) *Exercise concepts, calculations and computer applications* Benchmark Press, Carmel

Saltin B, Hermansen L (1966) *Oesophageal, rectal and muscle temperature during exercise.* J Appl Physiol 21:1757-1762

Settels JJ, Wesseling KH (1985) *Fin.A.Press: non-invasive finger arterial pressure waveform registration.* In: Orlebeke JF, Mulder G, van Doornen LJP (eds) Psychophysiology of cardiovascular control; models, methods and data. Plenum Press, New York, pp 267-283

Stolwijk JAJ (1971) *A mathematical model of physiological temperature regulation in man.* Report of NASA contractor CR 1855. Available from Pierce Foundation, New Haven, CT

Wenzel HG, Schwarzemau P (1989) *Evaluation of tolerance limits for humans under heat stress and the problems involved.* Scand J Work Environ Health [Suppl 1] 15:7-14

5

The relevance of individual characteristics for human heat stress response is dependent on work intensity and climate type

Chapter 5

The relevance of individual characteristics for human heat stress response is dependent on work intensity and climate type

George Havenith · John Coenen · Lyda Kistemaker · W. Larry Kenney

(accepted by Eur. J. Appl. Physiol.)

SUMMARY. Multiple heterogeneous subject groups (both genders and large variations in $\dot{V}O_{2\,max}$, body mass, body surface area (A_D), % body fat, and A_D/mass ratio) exercised on a cycle ergometer at a relative (%$\dot{V}O_{2\,max}$; REL) or an absolute (60W; ABS) work intensity in a cool (CO; 21°C, 50%r.h.), warm humid (WH; 35°C, 80%) and a hot dry (HD; 45°C, 20%) environment. Rectal temperature (T_{re}) responses were analysed for the influence of individual characteristics, environment and work intensity. Exposures consisted of 30 min rest, followed by 60 min work.

T_{re} was negatively correlated with mass in all conditions. Body mass acts as a passive heat sink in all the tested conditions. While negatively correlated with $\dot{V}O_{2\,max}$ and $\dot{V}O_{2\,max}$/kg in most climates, T_{re} was positively correlated with $\dot{V}O_{2\,max}$ and $\dot{V}O_{2\,max}$/kg in the WH/REL condition. Thus, when evaporative heat loss is limited as in WH, the higher heat production of fitter subjects in the REL trials determines T_{re} and not the greater heat loss efficiency associated with high $\dot{V}O_{2\,max}$. Body fatness significantly affected T_{re} only in the CO condition, where, with low skin blood flows (measured as increases in forearm blood flow), the insulative effect of fat is pronounced. In the warmer environments, high skin blood flows offset the resistance offered by peripheral adipose tissues. Contrary to other publications, T_{re} was positively correlated with A_D/mass ratio for all conditions tested. For both exercise types used, being big (a high heat loss area and heat capacity) is apparently more beneficial from a heat strain standpoint than having a favourable area to mass ratio (A_D/mass; high in small subjects). The total amount of variance in T_{re} responses which could be attributed to individual characteristics was dependent on the climate and work type. Though substantial for absolute work loads (52-58%) the explained variance in T_{re} differed strongly for relative loads: 72% for the WH climate with its limited evaporative capacity, and only 10-26% for the HD and CO climate. The results showed that individual characteristics play a significant role in the determination of body core temperature response in all conditions tested, but their contribution is low for relative work loads when evaporative heat loss is not restricted. This study demonstrates that effects of individual characteristics on human heat stress responses cannot be interpreted without taking into consideration both the heat transfer properties of the environment and the metabolic heat production resulting from the exercise type and intensity chosen. Their impact varies substantially between conditions.

5.1 Introduction

Large inter-individual differences in human responses to exercise in the heat have been described in literature (Kenney, 1985; Wenzel et al., 1989; Havenith et al., 1995a,b), differences which can in part be ascribed to differences in specific personal characteristics of the subjects tested. Research aimed at elucidating the effect of individual characteristics such as age, sex, body size, adiposity, and aerobic power has been extensive. Several recent studies have proposed that aerobic power, adiposity, and anthropometrics are the main determinants for heat stress response and that most effects observed in relation to age and gender differences are really due to concomitant differences in the first three mentioned parameters (Pandolf et al., 1988; Kenney and Havenith, 1993; Havenith et al., 1995a,b;).
Limited attention has yet been given to the question how these individual differences influence thermal responses for different exercise intensities or climate types. Common paradigms in thermophysiological research are the use of hot-dry versus warm-humid climates, both with equal thermal load, as e.g. defined by the WBGT (Wet Bulb Globe Temperature), or the use of fixed exercise intensities for all, versus a load relative to the individuals' maximum.
As to the exercise type: the widely accepted concept that exercise body core temperature is determined by the relative exercise intensity (Åstrand, 1960; Saltin and Hermansen, 1966) and sweat loss by absolute workload (Drinkwater and Horvath, 1979), has been shown not to be generalizable -- individual characteristics contribute significantly as well (Havenith et al., 1995b). For the climate, indications that an interaction between individual characteristics and climate type was present was suggested in experiments on male-female differences in exposure to hot-dry and warm-humid heat stress: e.g. the higher body surface to body mass ratio for females was suggested to be an advantage in the warm-humid climate, but not in the hot-dry climate (Shapiro 1980).

In many cases experiments published in literature, using different exercise modes (relative versus fixed load) and climate types are difficult to compare for the effect of individual differences due to differences in the characteristics of the subject groups used. Therefore the present study attempts to compare body core temperature data from 5 experiments on comparable subject groups, but performed in different climates (Cool, Warm-Humid and Hot-Dry), and with different exercise intensity types (a fixed load for all subjects and a workload relative to the individuals' maximal aerobic power). The data from these studies were analysed for the contribution of individual characteristics to the thermoregulatory response, and more specific, looked at possible interactions between the effect of individual characteristics, the exercise intensity type, and the climate type. The questions asked were therefore: "how much of the differences in heat stress response can be explained by selected individual characteristics? What is the relative contribution of different parameters

quantitatively? is it the same in different climates and for different work types?"
In order to compare the influence of several individual characteristics simultaneously, instead of one in each experiment as common in most previous research on individual characteristics, heterogeneous subject groups were used, with multiple regression as analysis method. This technique was previously described in this journal by Havenith and van Middendorp (1990) and Havenith et al., (1995a,b).

5.2 Methods

This paper presents an integrated analysis of the combined data from five separate experiments covering various combinations of climate and work intensity.
Two types of work intensity were used in the experiments, a fixed absolute intensity (ABS) of 60 watt on a reclining cycle ergometer for 60 min after 30 min rest, and an intensity relative to the individuals' maximal capacity (REL; a ramp exposure of 30 min each at rest, 25, and 45% $\dot{V}o_{2\,max}$ in sequence). For the analyses, only the final values of each test were used.
Three types of climate were used: a warm humid (WH: 35°C, 80% r.h.) and a hot dry (HD: 45°C, 20% r.h.) climate, both with similar WBGT value (±31.6°C) and a cool climate (CO: 21°C, 50%). All without added radiation and an air velocity < 0.2 $m \cdot s^{-1}$.
For the ABS trials, subjects were exposed to WH and HD. For the REL experiments, subjects were exposed to WH, HD, and CO.

Three groups of subjects of mixed gender were tested. One group participated in all REL tests (n=24), another participated in the WH/ABS condition (n=27), and a third group in the HD/ABS condition (n=30). Subject groups were recruited using the same criteria to allow between-groups comparisons. With the obvious exception of climate and work intensity, comparable procedures and methods were used in all experiments. Differences in methods were due to differences in available equipment at the time when the tests were performed. For reasons of readability and length of the text, only a general overview of methods is given here. A more detailed description of the methods of the separate tests is given in appendix A. Of the mentioned studies, data of 4 (CO/REL, HD/REL, WH/REL and WH/ABS) were published previously (Havenith and van Middendorp, 1990; Havenith et al., 1995a,b), with emphasis on the one condition used. The data for the condition HD/ABS and the discussions on the interaction between individual parameters, climate and work type are new.

Screening

In the screening procedure before the actual exposures, the subjects' individual characteristics were determined. Subjects were all volunteers, and studies were all approved by the Institute's Medical Ethics Committee. Before participation, each subject gave informed consent and was medically screened. This screening included

medical questionnaires or a full physical examination. The following individual characteristics were determined: anthropometric data (height and mass), body surface area (A_D), $\dot{V}O_{2\,max}$, average skinfold thickness (of 4 sites) and adiposity, and finally habitual physical activity level (ACTIV) using a validated questionnaire.
Natural heat acclimatization of all subjects was presumed to be equivalent, as all tests were performed in the spring and subjects had not been exposed to heat for several months. Exercise induced acclimation was controlled for by the use of the activity score mentioned above.

Heat stress test

For all heat stress tests, each subject reported to the lab, changed into shorts (women also wore a haltertop) and had sensors attached. Next they entered a climatic chamber set at the conditions for the WH, HD or CO climate. Wind speed was below 0.2 $m \cdot s^{-1}$. Subjects rested for 30 minutes in a semi-reclining chair mounted behind a cycle ergometer, followed by exercise (ABS or REL) for 60 minutes on the cycle ergometer, or until reaching one of the safety criteria [rectal temperature (T_{re}) > 39°C or HR > 90% of the individual maximum as determined in the aerobic power test, or any adverse symptomology].

Physiological variables were measured and stored using a calibrated data acquisition system: rectal temperature (T_{re}), mean skin temperature (T_{sk}), heart rate (HR), and oxygen uptake ($\dot{V}O_2$). Body heat storage was calculated from T_{re} and T_{sk} as: Store=$c_b \cdot [0.8 \cdot (T_{re}-37.) + 0.2 \cdot (T_{sk}-34)]$ ($J \cdot g^{-1}$), with C_b as average heat capacity of body tissue defined as c_b=[(fat mass/body mass)·2.51 + (body mass-fat mass)/body mass·3.65] ($J \cdot g^{-1} \cdot °C^{-1}$). Sweat loss was determined by weighing subjects before and after the heat exposure, corrected for metabolic and respiratory mass losses. Forearm blood flow (FBF), mean arterial pressure (MAP) and forearm vascular conductance (FVC) were determined also, but will be reported separately.

Data were stored at 60 second intervals. The final statistical analysis were performed using the data points collected at and averaged over the last 3 minutes of the test.

Statistics

For the statistical analysis, correlation and multiple regression analysis modules of the package "SYSTAT" (Wilkinson, 1990) and STATISTICA (1995) were used. Distributions of data were tested for normality using probability plots and skewness and kurtosis calculations. Differences in correlation coefficients between physiological responses and individual characteristics were tested only for comparisons within the climate type (WH/REL vs WH/ABS and HD/REL vs HD/ABS) or within an intensity (CO/REL vs WH/REL vs HD/REL and WH/ABS vs HD/ABS). For the correlation, significance levels of $p<0.05$ were accepted. p-values between 0.05 and 0.1 were considered as a trend.

The multiple regression analysis was performed in a stepwise, interactive, mode. Outliers were identified using studentized residuals and Cook's D-statistic. Parameters were included based on their correlation with the residual ($p<0.1$), and their inter-correlation (tolerance) with parameters already in the equation. The regression equations produced were accepted at a significance level of $p<0.05$.

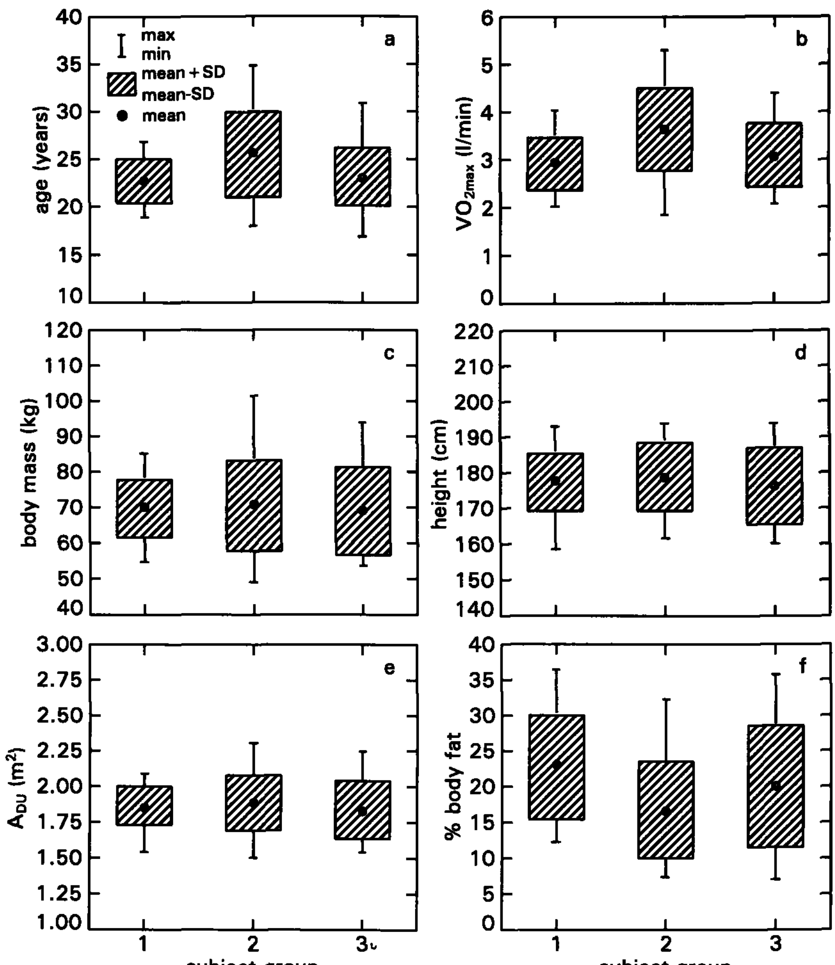

Fig. 1 Mean, standard deviation (sd), minimum and maximum values for physical and physiological characteristics of the subject groups used in the analysis. % body fat = fat percentage; A_D = body surface area. Group 1 = all REL conditions; group 2 = WH/ABS; group 3 = HD/ABS. See text for conditions.

For comparison of the importance of different parameters in relation to each other, standardized regression coefficients were used (Havenith, 1990). The value of the standardized regression coefficient represents the change in the dependent variable (e.g. T_{re}) expressed in units of its standard deviation, when the independent parameter (mass, $\dot{V}O_{2\,max}$, etc.) changes by 1 standard deviation. With this method, problems in comparing the effect of different parameters related to differences in their ranges and in the units in which they are expressed are solved. Using the standardized regression coefficients, the relative contribution of the different parameters to the explained variance was calculated as (see also chapter 1):

$$\text{contribution to } r^2 = \frac{|\text{standardized regression coefficient for parameter}|}{\sum |\text{all standardized regression coefficients in equation}|} \cdot r^2$$

Presented are "adjusted" r^2 values; which are r^2 values adjusted for the number of cases and the number of parameters in the analysis. These are lower than the regular r^2 value.

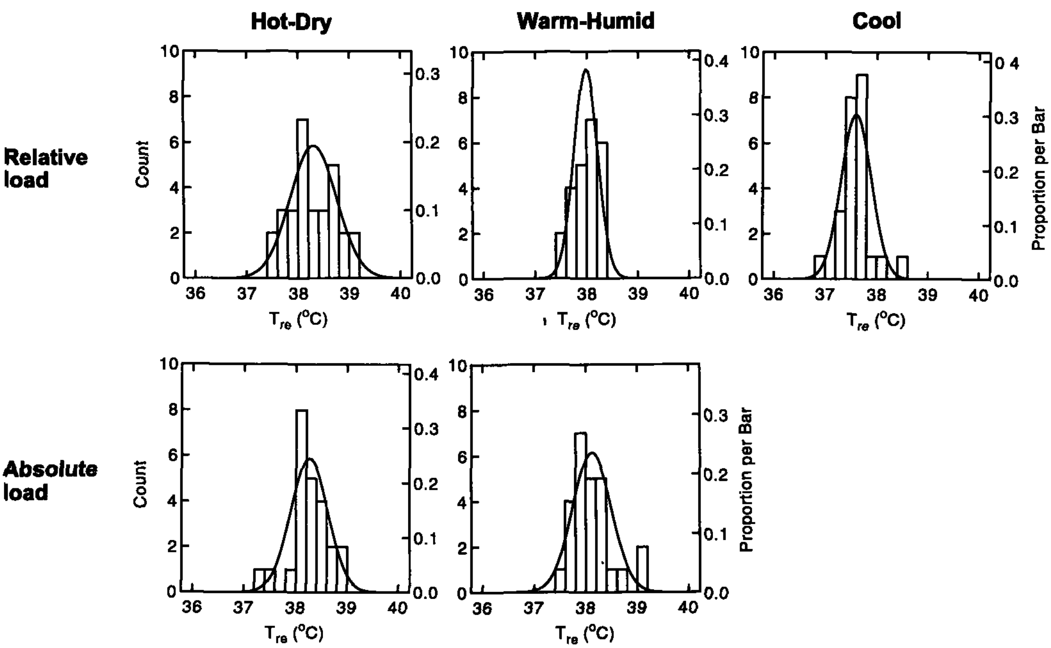

Fig. 2 Distribution of T_{re} at the end of the heat exposures for the different conditions. The drawn curves represent normal distributions with same average and standard deviation as the observed results.

5.3 Results

The subject group (Appendix A) characteristics are presented in Fig. 1. Subject groups did not show any significant difference in personal characteristics, thus allowing a good comparison between experiments. Though an attempt was made to minimize correlations between individual characteristics within groups by subject selection, $\dot{V}O_{2\,max}$ and mass were significantly correlated. Thus, these parameters had to be treated with caution in the analysis. Also, it could obviously not be avoided that body surface area was related to mass and height. $\dot{V}O_{2\,max}$, expressed per kg of body weight did not show any correlation with mass, however. Also body fat % was not correlated with $\dot{V}O_{2\,max}$, body mass, or body surface area.

The physiological response to be discussed is T_{re}, as a representative of body core temperature. The distribution of this response, as measured at the end of the exposures, together with a normal distribution with same average and SD is illustrated in Fig. 2. The individual characteristics to which it will be related are: $\dot{V}O_{2\,max}$, $\dot{V}O_{2\,max}$/kg, body mass, body fat %, body surface area, and surface to mass ratio. As the amount of data/relations to be presented in this paper is quite large, we have chosen to focus on the effects which showed a difference between climate types or between work intensities. The most interesting (and significant) differences will be illustrated in the graphs.

correlation analysis

In Fig. 3a the correlation coefficients of the relation between T_{re} and $\dot{V}O_{2\,max}$ are given for the five climate/intensity conditions. For ABS, significant negative correlations were present; for REL, only the positive correlation for the WH/REL condition approaches significance (p=0.08). This positive correlation for the WH/REL condition differs significantly from all other conditions, except from HD/REL, which difference approaches significance (p=0.08).

The relation between T_{re} and body mass is given in Fig. 3b. The relations (negative correlation) are similar for all trials in the heat (ABS and REL). For the cool climate the correlation was not significant. The relation of T_{re} with $\dot{V}O_{2\,max}$ standardized for body mass ($\dot{V}O_{2\,max}$/kg) are shown in Fig. 3c. In this case, only the correlation for the WH/REL was significant (WH/ABS approaches significance; p=0.07) and this WH/REL condition differs significantly from all other compared conditions. In Fig. 3d, the relation of T_{re} with body fat % is presented. Only for the CO/REL condition this positive correlation is significant, and significantly different from WH/REL.

The relation of T_{re} and A_D was similar to that for T_{re} and body mass. Also the relations between T_{re} and A_D/mass were similar to those between T_{re} on one hand, and mass or A_D on the other, but the sign was opposite. A higher A_D/mass ratio resulted in a higher T_{re}.

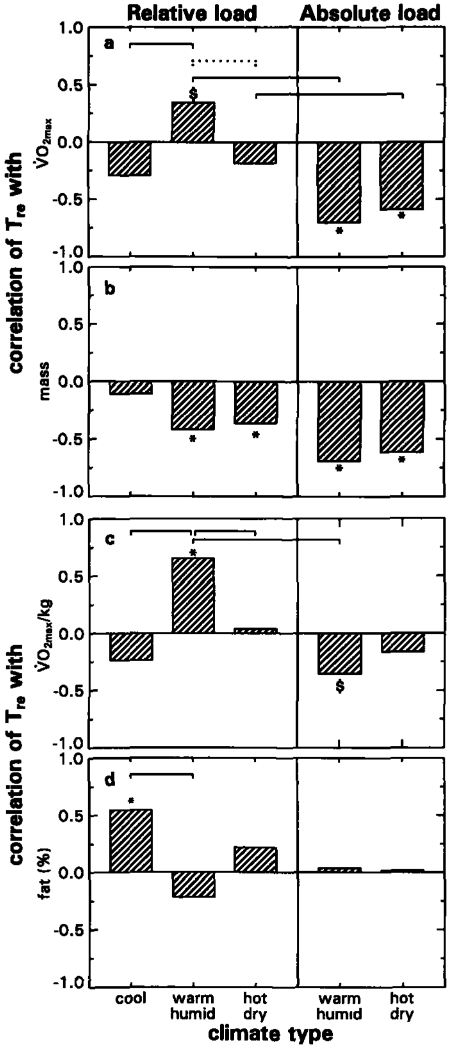

Fig. 3 Correlations of rectal temperature (T_{re}) with -a- maximal oxygen uptake ($\dot{V}O_{2\,max}$), -b- body mass, -c- maximal oxygen uptake per kg of body mass ($\dot{V}O_{2\,max}$/kg), and -d- body fat %. * = $p < 0.05$; $ = $0.05 < p < 0.10$; lines connect conditions which are significantly different (comparison within climate or work type only; see methods). Dotted line: *difference* at $0.05 < p < 0.10$ level.

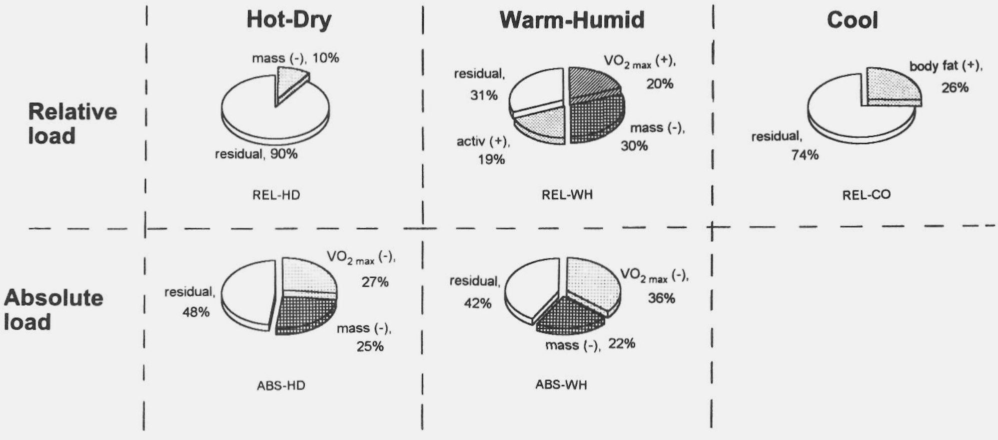

Fig. 4 Results from multiple regression analysis of rectal temperature response, starting with $\dot{V}O_{2\,max}$. Pie charts show amounts of explained variance in T_{re} (adjusted r^2) due to individual characteristics, and the unexplained variance. mass=body mass, ACTIV =regular activity score; (+) = positive correlation, (-)=negative correlation; REL=relative work load, ABS=Absolute work load, CO=Cool, WH=warm humid, HD=hot dry climate.

Multiple regression analysis

In Fig. 4 and 5, a selection of the results for the multiple regression analysis is presented as pie charts. The presented pie charts show the percentages of explained and unexplained variance due to individual characteristics in the data for T_{re} for the respective conditions. The percentage of explained variance (=adjusted r^2) is distributed over contributing parameters according to the size of their standardized regression coefficients as discussed in the methods.

In Fig. 4 the analysis was started with $\dot{V}O_{2\,max}$, being a relevant parameter in the correlation analysis. In that case, mass usually was the second relevant parameter, or for HD/REL, the only parameter. For CO/REL, body fat content was the only parameter.

It was also possible to develop equations including the A_D /mass ratio instead of mass. These equations produced very similar explained variances to those with mass. The relevant difference was that A_D /mass had a positive regression coefficient, whereas mass had a negative.

The results of the analysis pointed at an inter-correlation between $\dot{V}O_{2\,max}$ and mass in the regression equation (tolerance = 0.35). When the analysis is started from $\dot{V}O_{2\,max}$/kg (Fig. 5) this problem of a correlation with mass is not present (tolerance >0.95), providing a statistically more robust analysis. Also in this analysis, mass was the best predictor in sequence, except for HD/REL and CO/REL. In these conditions, $\dot{V}O_{2\,max}$/kg was not contributing at all.

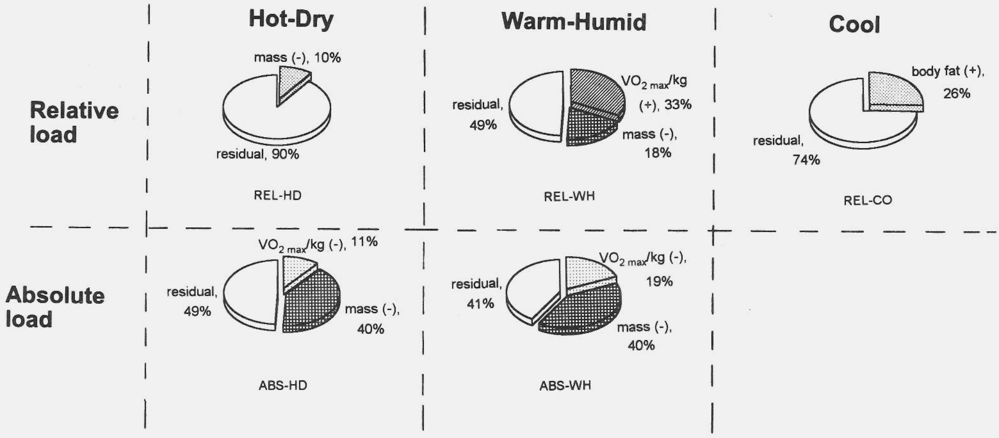

Fig. 5 Results from multiple regression analysis of rectal temperature response starting with $\dot{V}O_{2\,max}$/kg. For further explanation see Fig. 4.

Identical to the observation in the correlation analysis (Fig. 3), the contribution of $\dot{V}O_{2\,max}$ or $\dot{V}O_{2\,max}$/kg is opposite in sign between the WH/REL condition versus all others. In the WH/REL condition a higher $\dot{V}O_{2\,max}$ or $\dot{V}O_{2\,max}$/kg results in higher T_{re} values and in all other measured conditions in lower T_{re}'s.

Analysis of body heat storage in the same way provided almost identical results, with similar explained variance numbers and identical contributing parameters. In this case, however, none of the individual parameters contributed in the CO/REL condition.

5.4 Discussion

Methodology

The methodology of using heterogeneous subject groups, including males and females, instead of groups matched for all but one parameter was discussed by Havenith et al., (1995a). In this type of experiments, analysis by multiple regression is used. For the present approach, aiming at comparison of responses over climates and work load types and their combinations, the choice was made to present the data first in a simple correlation analysis approach to get an overview of the relevant factors, followed by the multiple regression analysis which usually includes less parameters.

Subject groups were chosen with a large variation in individual characteristics ($\dot{V}O_{2\,max}$, $\dot{V}O_{2\,max}$/kg, mass, A_D, A_D/mass, adiposity, regular activity level) within each group. Both genders were included, but not analysed separately. This decision was based on conclusions of numerous previous publications (e.g. Avellini and Kamon, 1980; Frye et al., 1981, 1982: Havenith and van Middendorp, 1990), that gender differences in thermoregulatory response during exercise and heat exposure are in fact due to differences in fitness and anthropometry. Gender differences observed at rest, related to e.g. hormonal differences, have been shown to disappear during stress (Frye et al., 1981). Also in the present study, once data are corrected for effects of other individual characteristics, no effect of gender could be observed. Inclusion of both genders resulted in a wider variation in individual characteristics within the subject groups than would have been possible with a single gender.

Between the groups used in the different experiments, the ranges of the individual characteristics ($\dot{V}o_{2\,max}$, mass, height, fat %, age, A_D) as well as their mean and standard deviations, were similar and not significantly different (Fig.1). Further, though some measuring methods for the definition of the individual characteristics differed between groups (e.g. $\dot{V}o_{2\,max}$; Table 1), the ranking of individuals for these parameters is expected to be equal between methods for the type of subjects used (no athletes). Therefore, correlations between responses and individual parameters are valid measures for comparison over climates and work types.

Experiments were sufficiently long to allow development of typical (heat) stress responses.

As $\dot{V}o_{2\,max}$ and mass were significantly correlated in all data sets, these parameters had to be treated with caution in the analysis. In part, this was approached by standardizing $\dot{V}o_{2\,max}$ for the mass effect, using $\dot{V}o_{2\,max}$/kg, which does not show a correlation with mass.

For each level of $\dot{V}o_{2\,max}$ a large variation in masses was present. This explains why it was possible that different effects for $\dot{V}o_{2\,max}$ and mass were observed (Fig. 3a vs 3b) even though they were correlated, as will be discussed below. Body fat % on the other hand was not correlated with $\dot{V}o_{2\,max}$ or with body mass, or A_D, due to selection of subjects within the test groups (Havenith et al., 1995b), allowing an unbiased comparison of these effects.

Results presented are those for rectal temperature response. Depending on the ideas of authors on thermoregulation (regulation around a setpoint versus regulation of body heat content), they choose for analysis of core temperature versus total body heat storage. For the presented experiments, as mentioned in the results, observations for body heat storage were almost identical to those for T_{re}. For this reason body heat storage analysis was not presented separately.

correlation analysis

rectal temperature and aerobic power. A clear difference in the relation between T_{re} and aerobic power ($\dot{V}o_{2\,max}$ or $\dot{V}o_{2\,max}$/kg) for the five climate/work intensity conditions was observed (Fig. 3a,c). For the ABS work loads, a significant negative correlation exists in both climates for the correlation with $\dot{V}o_{2\,max}$. This is almost significant for the

WH/ABS condition (p=.07) and insignificant for the HD/ABS condition when aerobic power is expressed as $\dot{V}O_{2\,max}$/kg.
For the REL work loads, where according to literature (Åstrand, 1960; Saltin and Hermansen, 1966) one would expect no correlation between T_{re} and aerobic power, significant correlations are still present. Furthermore these differ between climate types. While for REL only insignificant negative correlations are present for the cool and hot dry climate, a positive correlation is observed for $\dot{V}O_{2\,max}$ ($p<0.1$) and for $\dot{V}O_{2\,max}$/kg (significant) in the warm humid climate. The higher the subject's aerobic power, the higher the T_{re} in this condition. These findings can be explained as follows: For the ABS work load, the heat liberation in all subjects (assuming equal mechanical work efficiencies) is equal. Any advantage in heat loss capacity of fitter subjects in all climates will thus become visible as a reduced T_{re}. This was indeed observed (Fig. 3a). For the relative work load, the heat liberated in the body is dependent on the subjects $\dot{V}O_{2\,max}$. The subject's heat dissipation capabilities are also positively related to his $\dot{V}O_{2\,max}$ (Avellini et al., 1982, Yoshida et al., 1995). Thus if these two relations were equally strong, no correlation should be found between T_{re} and $\dot{V}O_{2\,max}$ for relative work loads. The latter is the case for the CO/REL and the HD/REL condition, where the effects of $\dot{V}O_{2\,max}$ on heat production and on heat loss are apparently balanced. In the used warm humid climate, however, the heat dissipation from the body is not limited by the body's capacity for heat loss (e.g. sweat rate), but by the climate. Due to the high vapour pressure the evaporative capacity of the environment is strongly reduced in this climate. In this case subjects with a high $\dot{V}O_{2\,max}$ will have a high work load and high heat production in the body, but they are unable to dissipate substantially more than less fit subjects due to climatic restrictions. Therefore T_{re} will rise with heat production. Consequently T_{re} also rises relative to $\dot{V}O_{2\,max}$.

rectal temperature and body size: For the relation between T_{re} and body mass (Fig. 3b) one might say that for the conditions used, in general, the bigger the body (larger mass, but also larger A_D), the smaller the increase in T_{re}. However, the interpretation of this finding is critical as positive correlations between body mass and $\dot{V}O_{2\,max}$ were present in the subject groups. Thus one might argue that the mass effect is not due to e.g. the higher heat storage capacity or high A_D which is concomitant with high mass, but acts through the mechanisms associated with the concomitant high $\dot{V}O_{2\,max}$, or vice versa. Surprisingly however, the relations of mass and $\dot{V}O_{2\,max}$ with T_{re} are not similar for all conditions: they are opposite in sign for the WH/REL condition, but have the same sign in all others. This can be explained as follows: for the ABS loads the effect of $\dot{V}O_{2\,max}$ and body mass on T_{re} work in the same direction: While the aerobic power level affects the active processes of heat dissipation (higher sweat output etc., resulting in a negative correlation with T_{re}), body mass has (for the cycling exercise used) a more passive effect: when heat accumulates in the body,

the rise in T_{re} will be lower when heat capacity of the body (≈mass) and cooling area (≈A_D) are higher. For the REL loads, where the effect of $\dot{V}O_{2\,max}$ is the results of the balance of improved heat dissipation and of increasing heat production with increasing $\dot{V}O_{2\,max}$, the net effect is dependent on the climate type. When the climate limits heat loss, the effect on heat production will prevail over that on heat dissipation, as described earlier. A high $\dot{V}O_{2\,max}$ will therefore be a disadvantage when working at a relative load in a WH climate, producing a positive correlation of T_{re} with $\dot{V}O_{2\,max}$. A big mass however will still imply a high heat storage capacity and thus the correlation of T_{re} with mass, as a separate parameter, remains negative.
This difference between conditions is strongly visualized in Fig. 3c, where the correlations of T_{re} with the ratio of aerobic power to body mass are presented. $\dot{V}O_{2\,max}$/kg and mass are not correlated in the subject groups, thereby avoiding the interpretation problems discussed before. However, the aggravating effect of a high aerobic power for heat strain in the WH/REL condition is even more pronounced when this mass correction on $\dot{V}O_{2\,max}$ is applied.

While T_{re} shows a negative correlation with both A_D and mass, a positive correlation (r=0.3-0.45 for HD and WH) was present with the surface to mass ratio of subjects (A_D/mass). This is strongest for the ABS conditions and slightly lower for the REL conditions. The higher the surface to mass ratio (the smaller the subject) the higher also T_{re}. This observation is consistent over all conditions in the current experiments (all significant, except the cool climate). Apparently, for cycling exercise, a high value of mass and A_D (heat storage capacity and cooling surface respectively) as found in big subjects is more beneficial in reducing heat strain than a high ratio of the two (high cooling surface area for a low heat producing mass) as found in small subjects is.
The observation described above, though supported by earlier results (Austin and Ghesquiere, 1976), is opposite to classical (evolutionary) descriptions of the relation between core temperature and A_D/mass. According to Bergman's (1847) and Allen's (1907) rules, a negative correlation between core temperature and A_D/mass for heat exposure is expected. Most earlier studies on this subject (Shvartz et al., 1973; Shapiro et al., 1980; Austin and Lansing, 1986) indeed observed such a negative correlation between T_{re} and A_D/mass for warm humid climates or work in vapour barrier clothing. Re-evaluating the data of those studies showed that a methodological problem might be present in the comparison of these different experiments. They all used a treadmill walking protocol, with fixed speed and a grade. The smaller the subject (low mass; high A_D/mass), the lower the metabolic rate. E.g. in Shapiro et al.,'s (1980) experiment the high A_D/mass groups (difference in A_D/mass ±10%) showed a 27% lower metabolic rate than the low A_D/mass group. Thus it is not unlikely that the lower heat load in the small subjects was responsible for the lower increase in T_{re}, and not the high A_D/mass ratio in these subjects. In our comparable WH/REL condition, differences in metabolic rate between low and high A_D/mass

groups were insignificant. Thus, as heat loss in WH is strongly limited, equal metabolic rates will result in higher T_{re} for the small subjects due to their smaller storage capacity. Thus in our opinion, the negative correlation of T_{re} with A_D /mass observed in the mentioned walking type experiments, was actually due to the substantial differences in metabolic rate between different A_D /mass groups and was incorrectly generalized to all heat stress conditions. Shvartz et al., (1973) already pointed at this alternative explanation of their findings. Also, the validity of Bergman and Allen's rule for use on a single species (man) was questioned and criticized (Scholander, 1955). Though it may be valid for resting conditions in cool environments, it was shown to be invalid during heat exposure (Schreider, 1975). Thus a high A_D /mass ratio as present in small subjects is by itself a disadvantage for the ability to cope with heat stress during exercise.

rectal temperature and body fat: A significant effect of body fat on T_{re} (high fat% - high T_{re}) was only observed in the CO condition. If one considers fat as a potential insulative layer, this insulating effect will be strongly dependent on the blood perfusion of this layer (Burse, 1979; Havenith, 1985). In the CO climate, measured forearm blood flows, taken as representative for skin blood flow, were low (maximum 7 ml/100ml/min). In this case fat could exert its insulating effect, resulting in higher body temperatures for the fatter subjects. For the warmer climates, FBF's were substantially raised (averages 14 to 21 ml/100ml/min). This shortcut for heat transport reduced the contribution to the heat resistance of the fat layer to virtually zero and thus resulted in insignificant effects of body fat on T_{re}. The latter finding is in accordance with observations of Burse (1979), who observed that differences in fat layers due to gender had no effect for exercise in the heat.

It should be noted that body fat in studies using weight bearing exercise (treadmill) may exert an effect on heat stress response through its passive mass, which has to be carried by the subject. The higher the passive mass, the higher the metabolic rate needed to carry it. This effect of increased heat production comes on top of the insulating effect. Also the specific heat of adipose tissue, in which water content is low, is about half that of the fat-free mass. Therefore, a given heat load per kg body weight will cause higher temperature elevations in the obese than in lean subjects (Bar-Or et al., 1969).

multiple regression analysis

The multiple regression analysis for T_{re}, using individual characteristics as independent parameters, showed large differences between the tested conditions (see results section and Fig. 4 and 5). Firstly, the total variance in the T_{re} data which could be explained by the individual characteristics tested (100-unexplained variance in Fig. 4 and 5) showed a wide range. The highest explained variance was found for the WH conditions: 58 (ABS) to 69% (REL). The lowest (10-26%) were found in those REL conditions where evaporative heat loss was not the climates' limiting factor (HD and CO). Secondly, though the sign of the contribution of several parameters was equal over conditions (mass (-, Fig. 3b), A_D (-), A_D /mass (+)), that of $\dot{V}o_{2\,max}$ or $\dot{V}o_{2\,max}$/kg was negative in all conditions but the WH/REL (Fig. 3a,c). This was identical to the results of the correlation analysis, even with inclusion of more parameters simultaneously. This once more substantiates that aerobic power is relevant for body core temperature when work load is equal for all subjects (ABS). When workload is relative to the individuals' maximum, however, aerobic power does not contribute significantly to the T_{re} response when evaporative heat loss is not limited by the climate. When heat loss is limited (WH), a high aerobic power goes together with a high T_{re} when workload is relative.

Comparing the relative contributions of different parameters, Fig. 4 shows that $\dot{V}o_{2\,max}$ has a higher impact on T_{re} than mass in the ABS conditions, whereas mass is more relevant in the REL heat conditions. For $\dot{V}o_{2\,max}$/kg (Fig. 5) this is reverse: a smaller effect than mass in the ABS condition, but a much larger one (and opposite in sign) in the REL-WH condition.

In this last condition aerobic power is mainly representing the actual heat liberation in the body per kg body weight, whereas in the ABS condition, with its identical heat production for all, it represents the better heat loss capacity for subjects with higher aerobic power.

Mass, in all conditions contributes as a passive heat sink, and as mass and A_D could be exchanged in the analysis with little change in the results, mass also contributes through its relation with the heat exchange area (A_D). Thus big subjects with a high heat sink and a high heat exchange area (all other things being equal) are at an advantage in the conditions tested here.

The results show that individual characteristics play a significant role in the determination of body core temperature response in all conditions tested, but their contribution is low in the presented experiments for relative work loads where heat loss is not restricted. Typically, the conditions where individual characteristics explain a substantial part of the variance in T_{re} are those where heat loss is limited, and where the passive system characteristics (mass, A_D, A_D /mass) defining the size of the heat sink and the heat exchange surface are of importance.

general discussion

In order to understand the findings in terms of physiological and biophysical mechanisms, one may try to develop a general model of these responses, involving heat production, loss and storage. If one considers the body as a box with a certain mass, this mass determines the heat storage capacity as well as the heat loss area (=A_D). All other things being equal, a big subject will be at an advantage over a small subject.

Maximal heat production levels (related to total muscle mass) as well as heat dissipation mechanisms (sweat production, sweat evaporation efficiency) are related to $\dot{V}O_{2\,max}$ (Avellini et al., 1982, Yoshida et al., 1995). The net effect of $\dot{V}O_{2\,max}$ is dependant on the balance between heat production and heat loss. At ABS work loads, heat production is equal for all, and the higher heat loss efficiency of high $\dot{V}O_{2\,max}$ subjects then results in lower T_{re}'s. At REL work loads, the higher heat productions of high $\dot{V}O_{2\,max}$ subjects is balanced by the higher heat loss efficiency, resulting in the absence of a net $\dot{V}O_{2\,max}$ effect (Åstrand, 1960; Saltin and Hermansen, 1966). When the heat loss is limited by the climate, the balance even goes the other way in these REL conditions. The higher heat production of high $\dot{V}O_{2\,max}$ subjects directly results in higher T_{re}'s as seen in the present study.

Body fat and skin blood flow can be seen as parallel resistances between core and skin. Body fat is therefore only active as insulator when skin blood flow is low (high parallel resistance), as observed in the cool condition.

This simple model describes the findings well. In other conditions than studied here (e.g. walking at a certain speed and grade), an increase in mass and fat % also has indirect effects: it increases the (passive) mass that has to be carried and thereby metabolic rate. This leads to an increased T_{re} for big or obese subjects in those conditions. These effects are also covered by the mechanism presented above.

In conclusion, this study shows, that effects of individual characteristics on human heat stress response cannot be defined without taking into consideration the heat transfer properties of the climate used and the metabolic rate resulting from the type of workload. Taking this into consideration, seemingly contradictory results from different studies can be explained using a simple model. The results showed that individual characteristics play a significant role in the determination of body core temperature response in all conditions tested, but their contribution is low for relative work loads when evaporative heat loss is not restricted.

References

Allen JA (1906) *The influence of physical conditions in the genesis of species.* Ann Rep Smithsonian Inst 375-402

Anderson RK, Kenney WL (1987) *Effect of age on heat-activated sweat gland density and flow during exercise in dry heat.* J Appl Physiol 63:1089-1094

Åstrand I (1960) *Aerobic work capacity in man and women with special reference to age.* Acta Physiol Scand 49 [suppl 169]:1-92

Austin DM, Ghesquiere J (1976) *Heat Tolerance of Bantu and Pygmoid groups of the Zaire River Basin,* Human Biology 48:439-453

Austin, DM, Lansing, MW (1986) *Body size and heat tolerance: A computer simulation,* Human Biology, 58:153-169

Avellini BA, Kamon E (1980) *Physiological responses of physically fit men and women to acclimatization to humid heat.* J Appl Physiol 49:254-261

Avellini BA, Shapiro Y, Fortney SM, Wenger CB, Pandolf KB (1982) *Effects on heat tolerance of physical training in water and on land.* J Appl Physiol 53:1291-1298

Bar-Or, O, Lundgren HM, Buskirk ER(1969) *Heat tolerance of exercising obese and lean women.* J Appl Physiol 26, 403-409

Bergman C (1847) *Über die Verhältnisse der Wärmeökonomie der Tiere zu ihrer Grösse.* Göttinger Studien 1:595-708

Binkhorst RA (1993) *Different work load protocols, the effect on maximal work capacity and* $\dot{V}o_{2\,max}$ (in Dutch). Geneeskunde en Sport 26:146-147

Burse RL (1979) *Sex differences in human thermoregulatory response to heat and cold stress.* Human Factors 21:687-699

Drinkwater BL, Horvath SM (1979) *Heat Tolerance and Aging.* Med Sci Sports Exercise 11:49-55

DuBois D, DuBois EF 1916) *Clinical calorimetry: a formula to estimate the appropriate surface area if height and weight be known.* Arch Int Med 17:863-871

Durnin JVGA, Womersly J (1974) *Body fat assessed from total body density and its estimation from skinfold thickness: Measurements on 481 men and women aged 16 to 72 years.* Br J Nutr 32:77-97

Frye AJ, Kamon E, Webb M (1982) *Responses of menstrual women, amenorrheal women and men to exercise in a hot, dry environment.* Eur J Appl Physiol 48: 279-288

Frye AJ, Kamon E (1981) *Responses to dry heat of men and women with similar aerobic capacities.* J Appl Physiol 50:65-70

Hardy JD, DuBois EF (1938) *The technique of measuring radiation and convection.* J. of Nutr. 15:461-475

Havenith G (1985) *Individual parameters in thermoregulatory control; a review.* Institute for Perception report IZF 1985-26

Havenith G, van Middendorp H (1990) *The relative influence of physical fitness, acclimation state, anthropometric measures and gender on individual reactions to heat stress.* Eur J Appl Physiol 61:419-427

Havenith G, Inoue Y, Luttikholt VGM, Kenney WL (1995a). *Age predicts cardiovascular, but not thermoregulatory, responses to humid heat stress.* Eur J Appl Physiol 70:88-97

Havenith, G, Luttikholt VGM, Vrijkotte TGM (1995b) *The relative influence of body characteristics on humid heat stress response.* Eur J Appl Physiol 70:270-279

Kenney WL (1985) *A review of comparative responses of men and women to heat stress.* Environmental Research 37:1-11

Kenney WL, Havenith G (1993) *Heat stress and age: skin blood flow and body temperature.* J Therm Biol 18: 341-344

Pandolf KB, Cadarette BS, Sawka MN, Young AJ, Francesconi RP, Gonzalez RR (1988) *Thermoregulatory responses of middle-aged and young men during dry-heat acclimation.* J Appl Physiol 65:65-71

Ross AM, Jackson AS (1990) *Exercise Concepts, Calculations and Computer Applications.* Carmel Benchmark Press

Saltin B, Hermansen L (1966) *Esophageal, rectal and muscle temperature during exercise.* J Appl Physiol 21:1757-1762

Schreider E (1975) *Morphological variations and climatic differences,* J Human Evolution 4:529-539

Scholander PF (1955) *Evolution of climatic adaptation of homeotherms.* Evolution 9: 15-26

Shapiro Y, Pandolf KB, Avellini BA, Pimental NA, Goldman RF (1980) *Physiological responses of men and women to humid and dry heat.* J Appl Physiol 49:1-8

Shvartz E, Saar E, Benor D (1973) *Physique and heat tolerance in hot-dry and hot-humid environments.* J Appl Physiol 34:799-803

Smolander J, Ilmarinen R, Korhonen O, Pyykkö I (1987) *Circulatory and thermal responses of men with different training status to prolonged physical work in dry and humid heat.* Scand J Work Environ Health 13:37-46

Statistica (1995) Statsoft Inc Tulsa OK 74104

Wenzel HG, Mehnert C, Schwarzemau P (1989) *Evaluation of tolerance limits for humans under heat stress and the problems involved.* Scand J Work Environ Health [suppl 1] 15:7-14

Whitney RJ (1953) *The measurement of volume changes in human limbs.* J Physiol (London) 121:1-27

Wilkinson L (1990) *SYSTAT: the system for statistics.* Evanston, IL: Systat Inc

Yoshida, T, Nakai S, Yorimoto A, Kawabata T, Morimoto T (1995) *Effect of aerobic capacity on sweat rate and fluid intake during outdoor exercise in the heat.* Eur J Appl Physiol 71:235-239

Appendix 1 Description of methods of the 5 experiments

condition	REL (HD, WH and CO)	WH/ABS	HD/ABS
subjects	*n=24; 12♂, 12♀*	*n=27; 19♂, 8♀*	*n=30; 14♂, 16♀*
Screening:			
$\dot{V}O_{2\ max}$	O_2 uptake measured by custom built closed circuit *oxygen system, using a polarographic oxygen analyser* (Servomex). Maximum determined by extrapolation of the results of an incremental exercise test on a Monark power regulated bicycle ergometer at submaximal levels of intensity (Åstrand and Rodahl 1986).	Maximal O2 uptake (Oxycon sigma, Mijnhardt) in incremental exercise test on treadmill with modified Balke protocol [2.5% gradient changes (=1.23 $W{\cdot}kg^{-1}$ at 5 $km{\cdot}h^{-1}$), every 2 min after 5 min warmup at 5% gradient, until exhaustion.	Maximal oxygen uptake ($\dot{V}o_{2\ max}$), was derived from the maximally achieved workload during an incremental exercise test on a Lode bicycle ergometer (Binkhorst, 1993)
Body fat content	Sum of 4 skinfolds (Durnin and Womersley, 1974)		
Body surface area	from height (±0.5 cm) and *mass* (±*10 g*) (DuBois and DuBois, 1916)		
Habitual activity	Questionnaire describing physical activity level and participation in exercise programs. Scored on a 7-point scale, ranging from "avoid walking or exertion" to "run over 10 miles each week or exercise over 3 h each week" (Ross and Jackson, 1990)		
Heat stress test			
Temperature/ Humidity/ Wind	WH: 35°C/80%/<0.2$m{\cdot}s^{-1}$ HD: 45°C/20%/<0.2$m{\cdot}s^{-1}$ *CO*: 21°C/50%/<0.2$m{\cdot}s^{-1}$	35°C/80%/<0.2$m{\cdot}s^{-1}$	45°C/20%/<0.2$m{\cdot}s^{-1}$
Work Load regime	30 min. rest on wire chair behind an electronically controlled cycle ergometer (modified, power regulated, Monark, Monark-Crescent AB, Varburg, Sweden) in a reclining position, followed by 30 min work at 25%$\dot{V}o_{2\ max}$, and 30 min work at 45%$\dot{V}o_{2\ max}$	60 watt on reclining bicycle (electrically braked Lode) for 60 min after a 30 min rest period	60 watt on reclining bicycle (electrically braked Lode) for 60 min after a 30 min rest period
$\dot{V}o_2$	*custom built* closed circuit oxygen system, using a polarographic oxygen analyser (Servomex)	oxygen uptake by analysis of expired gases during two 5-min periods (after 15-min and after 45-min work) using a Mijnhardt Oxycon Sigma system;	oxygen uptake by analysis of expired gases during two 5-min periods (after 15-min and after 45-min work) using a Mijnhardt Oxycon Sigma system;
Core temperature	Yellow Springs Instruments 700 Thermistor inserted 12 cm beyond anal sphincter		
Skin Temperature	Average skin temperature (T_{sk}) was calculated from seven (head, upper arm, lower arm, chest, back, upper leg, lower leg) separate measurements (Yellow Springs Instruments 700 skin Thermistors), weighted for the surface area they represent (Hardy/DuBois).	surface weighted average of 4 YSI 700 series thermistors placed on the arm, upper leg, chest and back (Hardy/DuBois).	surface weighted average of 4 YSI 700 series thermistors placed on the arm, upper leg, chest and back (Hardy/DuBois).
Heart Rate	The ECG (CM5 lead) was monitored continuously, from which HR was deduced and recorded		

Appendix, additional analysis

Intro

In addition to the analysis of T_{re}, also other physiological responses were analysed: skin temperature, heart rate, forearm blood flow, blood pressure, forearm vascular conductance and sweat loss.

Methods

Heat stress test: Cardiovascular variables were measured: Heart rate (HR) was determined from a CM_5 lead via a recorder and oscilloscope for constant monitoring; Forearm blood flow (FBF), was measured by venous occlusion plethysmography using a mercury-in-rubber strain gauge (Whitney, 1953), with temporary arterial occlusion of the hand during the measurement period; Mean arterial pressure (MAP) was determined by brachial auscultation and calculated as 0.67·diastolic pressure + 0.33·systolic pressure; Forearm vascular conductance (FVC) was calculated as FVC = FBF/MAP in units of $\%\cdot min^{-1}\cdot mm\ HG^{-1}$. Sweat loss was determined from the mass difference before and after the session.

Results

Skin temperature

The relationship between T_{sk} and $\dot{V}O_{2\,max}$ (Fig. B1a) is comparable to that of T_{re} (Fig. 3), except for the CO/REL condition. With all ABS conditions, subjects with higher $\dot{V}O_{2\,max}$ levels had lower skin temperatures, for HD/REL this is the same, but just insignificant (p=.08). Conversely, for REL in the warm humid climate, skin temperature is higher for subjects with higher $\dot{V}O_{2\,max}$. For the CO climate the positive correlation between T_{sk} and $\dot{V}O_{2\,max}$ approaches significance (p=0.07). The relation of T_{sk} with $\dot{V}O_{2\,max}$/kg is virtually the same as that with absolute $\dot{V}O_{2\,max}$. The correlations of T_{sk} with body mass and A_D are negative (insignificant for REL conditions) for all conditions. The picture of the relation of T_{sk} with body fat % (Fig. B1b) is almost the reverse of that of T_{sk} with $\dot{V}O_{2\,max}$ (Fig. 3a). The CO/REL condition differs significantly from the HD/REL condition.

Heart rate

The correlation of HR with $\dot{V}O_{2\,max}$ for the different climate/intensity types is shown graphically in Fig. B2a. For ABS, the correlation is negative and significant. For the REL conditions, no significant correlation between HR and $\dot{V}O_{2\,max}$ is present. REL conditions differ significantly from ABS conditions with no climate effect evident. A similar pattern is present in the correlation of HR with $\dot{V}O_{2max}$/kg, body mass (Fig. B2b) or A_D. Correlations of HR with body fat % are all not significant.

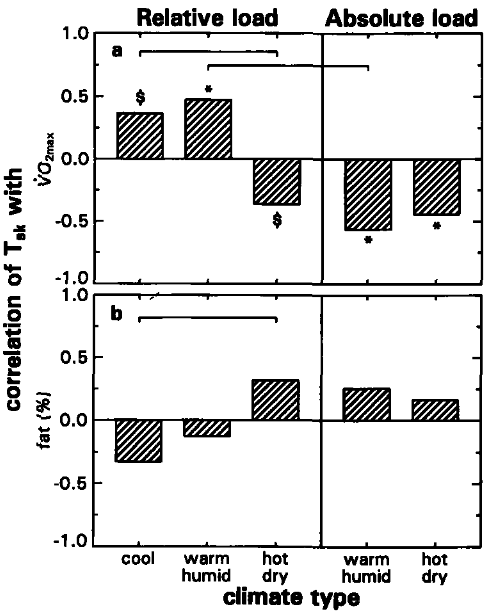

Fig. B1 Correlations of skin temperature (T_{sk}) with -a- maximal oxygen uptake ($\dot{V}O_{2max}$), and -b-body fat %. * = $p < 0.05$; $ = $0.05 < p < 0.10$; lines connect conditions which are significantly different (comparison within climate or work type only; see methods).

Blood flow and blood pressure

The relationship of FBF, MAP and FVC with $\dot{V}O_{2max}$ did not show significant differences among the climate and intensity types. Their relation with body mass is such that in CO/REL, FBF and FVC are significantly higher in heavier people (r =0.4) whereas in all other climates the relations are not significant. When $\dot{V}O_{2max}$ is expressed per kg of body mass, FBF correlates positive with $\dot{V}O_{2max}$/kg, except for CO/REL, where the correlation is almost zero. MAP is significantly higher with increasing mass in WH (r =0.52) and is not related to mass in other climates. FBF and FVC are also correlated to body fatness. This correlation is negative (r =-0.3 to -0.4), high fat is associated with low FBF and FVC (p<0.05 for ABS conditions) except for CO where the correlation is zero.

Sweating rate

Sweat rate shows a strong positive correlation with $\dot{V}O_{2max}$ (Fig. B3a), $\dot{V}O_{2max}$/kg, A_D, and mass across all conditions (r =0.4 to 0.8). When sweating rate is expressed per unit of body surface area, to correct for differences in body size between subjects, the correlations are reduced, but most remain significant. The correlation between sweating rate or sweating rate per unit surface area (Fig. B3b) and body fat % is not significant for the ABS conditions and negative in all REL conditions.

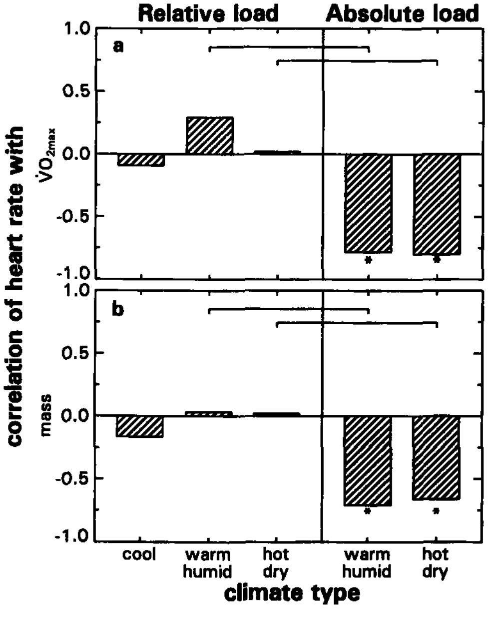

Fig. B2 Correlations of heart rate with -a- maximal oxygen uptake ($\dot{V}O_{2\,max}$) and -b- body mass, for the different conditions. * = $p < 0.05$; \$ = $0.05 < p < 0.10$; lines connect conditions which are significantly different (comparison within climate or work type only; see methods).

Discussion

Skin temperature

The relation between skin temperature and $\dot{V}O_{2\,max}$ reflects the same mechanisms as the relation of T_{re} with $\dot{V}O_{2\,max}$(Shapiro, 1980). When the work load is fixed, or in case of a hot dry climate, subjects with higher aerobic power have lower skin temperatures (more efficient evaporation due to higher sweat production and better sweat distribution) whereas for the relative load in the warm humid climate, where more sweating related to high $\dot{V}O_{2\,max}$ is not really effective, the skin temperature is higher for subjects with higher $\dot{V}O_{2\,max}$ and thus higher heat loads. Interestingly T_{sk} also is positively correlated (p=.07) with $\dot{V}O_{2\,max}$ for the CO climate. Absolute T_{sk} is much lower in this case than for the heat exposures (29.5 versus 36 - 38 °C) and the positive correlation is most likely a reflection of the higher skin blood flow, actually observed for subjects with higher $\dot{V}O_{2\,max}$ in this case.

Also for the CO/REL condition, Tsk shows a different correlation with body fat % than for the HD climate. Apparently, though the skin fat layer does not have an insulator effect on body core temperature in the heat, it has sufficient effect to show a trend of hotter skin in dry heat and cooler skin in cool environments with increasing fat %. Though the difference between these conditions is significant, both effects separately only approach significance.

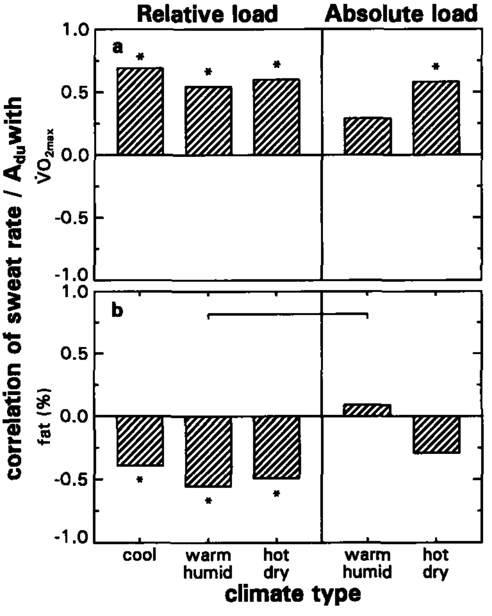

Fig. B3 Correlations of sweat rate with: -a- maximal oxygen uptake ($\dot{V}O_{2\,max}$) and -b- body fatness for the different conditions. * = $p < 0.05$; \$ = $0.05 < p < 0.10$; lines connect conditions which are significantly different (comparison within climate or work type only; see methods).

Heart rate

The correlation of heart rate with $\dot{V}O_{2\,max}$ for the different climate/work load types, as presented in Fig. B2 shows that correlations are insignificant except for the fixed work intensity, where the correlation is negative. This correlation is not unexpected (Smolander et al., 1987). The higher the subject's aerobic power, the lower that fixed work intensity will be in terms of the load on the person relative to his or her personal maximum. Thus also: the higher the $\dot{V}O_{2\,max}$ the lower the heart rate for a given intensity. At the relative work load, heart rates are expected to be equal for all subjects, assuming that they have similar maximal heart rates. Inspection of the data set did show a variability in maximal HR, but this was not related to $\dot{V}O_{2\,max}$. Equal HR are indeed the case for the cool and the hot dry climate. Only a small but insignificant positive correlation is present in the WH/REL condition. This could be related to the higher core temperatures of the fitter subjects in this situation, which necessitates a stronger thermoregulatory reaction, stronger skin blood flow, and thus a higher additional increase in heart rate to keep an adequate cardiac output. Heart rate represents, besides the effect of the actual work load, also the thermoregulatory effect of increasing skin blood flow during body temperature increase.

The correlation of HR with body mass is strongly negative for the fixed loads, which reflects the correlation of mass with $\dot{V}O_{2\,max}$. The higher the mass, the higher the $\dot{V}O_{2\,max}$. Also, the equal heat production for all subjects at a fixed load is distributed over a heat sink which is directly related to body mass. Thus, with a big mass T_{re} can remain lower and thus also the thermoregulatory increase in HR can remain lower too. For the relative loads, no significant correlation of mass with HR is present, supporting the explanation given above.

Other circulatory parameters

The relationship of FBF, MAP and FVC with $\dot{V}O_{2\,max}$, mass and body fat %, did not show significant differences between the climate types and work load types. Absolute levels of MAP for the warm and hot climate types are lower than for the CO climate, reflecting the lowered peripheral vascular resistance, which is not completely compensated by increased cardiac output (Smolander et al., 1987). In the CO/REL condition, the correlation of FBF and FVC with body fat is zero. Thus the above described higher T_{re} with high fat % in that climatic condition is not due to a lower FBF or FVC in subjects with high fat % but must be related to the insulative effect of the fat layer at the observed low FBF's.

Sweat rate

Body sweat rate and sweat rate per unit of body surface area show a distinct correlation with $\dot{V}O_{2\,max}$, but this is very similar for all conditions (Fig. B3). Though the correlation seems lower for the warm humid environment at the fixed intensity, these differences are not significant. Thus whether work intensity is fixed or related to the $\dot{V}O_{2\,max}$, a positive correlation of sweat production with $\dot{V}O_{2\,max}$ is present. Fitter people produce more sweat in all the conditions. The concept that sweat rate is related to absolute metabolic load or work rate (Drinkwater and Horvath, 1979) may hold true, but part of the variance in the data can still be attributed to the individuals' $\dot{V}O_{2\,max}$.

Conclusion

The observed responses for skin temperature, heart rate, circulation and sweat rate support the qualitative model proposed in the discussion of the main paper.

6

Thermal modelling of individual characteristics

Chapter 6

Thermal modelling of individual characteristics

George Havenith

Summary. One of the major gaps in the prediction of heat stress response is the limited implementation of individual characteristics in prediction models. Without this individualization, the evaluation of the resultant average group response prediction necessitates the use of very conservative limit values for body temperature increase. This is caused by the wide range of responses observed within a group.

The present study aimed at the implementation of individual characteristics in an analytical heat stress prediction model (THDYN), in order to investigate whether this would indeed result in a more precise prediction with less variance between predicted and observed responses. For this purpose, the relevant individual parameters related to anthropometric characteristics (body surface area [A_D], body tissue conductance, body heat capacity), sweating and skin blood flow control (training and acclimation) were introduced in the model. The control parameters were derived from literature.

Next, data sets which were not used for the parameter estimation were used for a validation of the new model. It was found that the individualized model indeed provided an improved prediction over a model where mean population parameters were used. The magnitude of the improvement varied with the climate and the work type, however. The best individual predictions for body heat storage were observed for fixed work loads in a warm, humid and in a hot, dry climate and for work loads relative to the individual maximum in a warm, humid climate (Explained variance 27 - 53%). For relative work loads in a cool and in a hot, dry climate the models predictive capacity for individuals was not significantly improved (<10%).

When this predictive power was compared to that of an empirical multiple regression model, derived from these specific data sets (the "maximal achievable" predictive power), using individual characteristics as independent parameters and body temperature as dependent variable, it was found that the analytical simulation model had between 54 and 89% of the predictive power of the empirical regression model, except for the cool climate where this ratio was zero.

It can be concluded that the additions to the analytical simulation model provide a good tool for study of effects of individual characteristics, but also that a substantial part of individual variation is still not understood.

6.1 Introduction

Numerical models of human responses to heat and cold exposure are widely used. Some of these models are empirical (Givoni and Goldman, 1972, 1973), others are restricted to heat balance calculations (ISO 7933, ISO TR 11079), or include a thermoregulatory system, including sweating and blood flow regulation (Nishi and Gagge, 1977; Stolwijk and Hardy 1977, Wissler, 1964, 1982) and some involve the physics of clothing (Werner 1989; Lotens, 1993; Werner and Webb, 1993). The validity of the predictions by various models is dependent on the combination of the climate, clothing and work load. One problem present in all models, however, is that even if their prediction is quite good for an average group response, the response of an individual may still show a large deviation from the prediction. The intention of the present paper is to incorporate individual aspects of thermoregulatory response in an analytical simulation model, and to determine whether this actually improves the prediction of heat stress responses of specific individuals in a population.
The importance of having an insight in the mechanisms behind the individual differences will be discussed in the next paragraphs. Thereafter the model used as starting point will be discussed as well as a description of the new model. This will be followed by an in detail description of the changes and additions to the original model. The chapter will be concluded by a validation of the new model, using the datasets of the previous chapters (which will not be used in the model's development!) as a basis, and by a comparison of the performance of the new model versus the original model, and versus the regression model of chapter 5.

6.2 The necessity of individualization

6.2.1 Safety limits

Safety guidelines for occupational exposure to climatic stress have set the deep body temperature limit at 38°C (ISO 7933). This is by itself not a dangerous temperature at all. Many people reach this temperature riding their bicycle to work. Unfortunately, in the past many people have used this temperature as a limit value for each individual worker. This is not the correct way to use this limit, however. To understand this we have to go back to the origins of this value.

The most cited document for the 38°C limit is a document of the WHO: in 1969, the World Health Organisation (WHO, 1969) stated that it was inadvisable to allow deep body temperatures to exceed 38°C in prolonged daily exposure to heavy work. However, this document also states that under constant surveillance of the individual

it is advised to stop exposure at 39°C. Further, both statements were based on conditions where core temperature (measured by rectal temperature (T_{re})) supposedly is a direct function of metabolic rate and independent of ambient temperature (T_a) i.e. for exercise without severe external heat stress. Thus they may not necessarily be valid for heat exposures, where the increase in T_{re} is not only caused by metabolic heat production, but by a hot climate as well.
Data from Wyndham and coworkers (Wyndham et al., 1965) made them conclude that during heat exposures, values for T_{re} above 39.2°C should be considered excessive and may rapidly lead to total disability in most men due to excessive, often disturbing, physiological changes.
From these sources, and the literature on heat stroke, two maximum T_{re}'s for an individual were adopted (Malchaire, 1996):

- 42°C as the maximum internal temperature to avoid physiological sequela (heat stroke),
- 39.2°C as the maximum temperature in normal work, to avoid heat exhaustion.

Performing equal work in equal climatic circumstances will not result in an identical T_{re} for all subjects, but in a Gaussian distribution of T_{re} (Havenith et al., 1997), which becomes positively skewed for longer heat exposures with high maximal T_{re}'s. (Wyndham et al., 1965). In order to avoid any subject to reach 39.2°C T_{re}, the average population T_{re} will therefore have to be much lower. Based on Wyndham's data, Malchaire (1996) analysed the chance for subjects to reach 39.2°C, for different mean T_{re} values for a group. He found that the chance for an individual to reach a T_{re} of 39.2°C was 10^{-4}, if the group mean was limited around 38°C, i.e. the WHO limit. Unfortunately, little information on the group characteristics for which the data were collected are available, so that these data are difficult to generalize to the full working population. Data from Havenith et al. (1990, 1995), where subject characteristics are well defined, will be analysed for the same purpose in the near future.

The approach followed by Malchaire gives a good idea of how the WHO may have wanted the limit of 38°C to be used: As long as the group mean does not exceed this value, it is unlikely that subjects at the extreme of the population will be at risk.

6.2.2 Safety limits in models

Predictive models, as e.g. ISO 7933 also aim at the prediction of a safe group response (i.e. 38°C maximal T_{re}) for 95 to 99% of the population. In the actual use of this model a different problem became apparent. When actual work places were evaluated, it was shown that according to ISO 7933 conditions in many workplaces in the mining industry were well above the model's safety limits (Kampmann, 1992).

However, at these workplaces few problems were encountered. One of the possible explanations is that workers at these locations are fitter than average and also acclimatized, resulting in a lower strain (i.e. T_{re}) for the same climatic stress compared to the average population. Thus, the limit values for climatic stress used may be far too conservative for this special group. This situation is schematically presented in Fig. 1. If the limit for the 95th percentile was set at 39 °C, the distribution of observed core temperatures for an average population in a hypothetical heat exposure might look as presented. The fit, acclimated miners would be situated at the left part of the distribution for the same climatic stress. It is clear that these have a low level of heat strain and thus are hardly stressed by the climate. The climatic stress limit for this group should be adjusted for the specific characteristics of this sub-population. The core temperature values (strain) of 39.2 °C as limit and 38 °C as mean may still be valid for the sub-group assuming a similar standard deviation in T_{re}'s (which may be questionable), but in any case conditions under which they will be reached are more severe than for the average population.

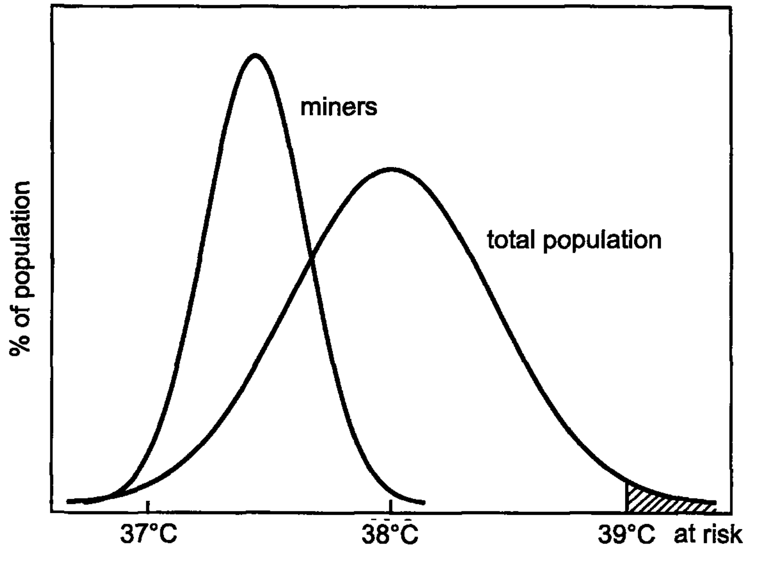

Fig. 1 Distribution of body core temperature in a general population exposed to an identical external exercise and heat load. The subgroup data represents the results for the miners in the same exposure.

The problem present here is the struggle between safety for all on one hand and productivity on the other. Its basis is the lack of knowledge on how to adjust the safety limits to the individual.
From the above it is obvious that there is a need to produce better predictions of heat stress response at the level of an individual. Only then can limits be used with a proper balance of safety and productivity.

The purpose of the present paper is to incorporate individual characteristics in a thermoregulatory model (THDYN; Lotens, 1993) using data from literature, and to validate the individualized model with data from heat exposure experiments from our laboratory (Havenith and van Middendorp, 1990; Havenith et al., 1995a,b, Havenith et al., 1997). The main research question is: "Can the prediction of heat strain by simulation models be improved by incorporation of individual characteristics".

6.3 The model

6.3.1 The original model

The model used as a starting point was described by Lotens (1993). It comprises a physiological part based on the Gagge (for detailed description see Gagge et al., 1971, 1986) two node[4] model, and a physical model describing the heat transfer characteristics of clothing. The physiological model contains a number of control functions for physiological processes, as well as the heat transfer properties of the human body. The principle is represented in Fig. 2. Core, skin and mean body temperature are used as input for several setpoint identified feedback loops controlling effector responses (skin vasoconstriction/dilation, sweat production, shivering). The effector responses together with metabolism due to exercise result in a certain heat loss or gain, which then affects the "passive" system (the body), resulting in a new body temperature (i.e. the feedback). The relation between effectors and resulting body temperature is affected by environmental parameters (heat transfer properties) and heat production levels (activity). The passive system itself is defined in terms of heat capacity, mass and surface area, which are constants in the original Gagge model.

[4]Two node model: the nodes represent the body core and the body shell. The core being the compartment with the regulated and defended temperature, the shell being the buffer between core and environment, whose temperature is determined by the heat exchanges with the core and with the environment. Lotens (1993) converted this into a five node model by dividing the skin node into a clothed versus an unclothed part, and these into a radiated area and a non radiated area. Heat transfer may be different in these area's, but control characteristics are identical, and in the current study the distinction is insignificant.

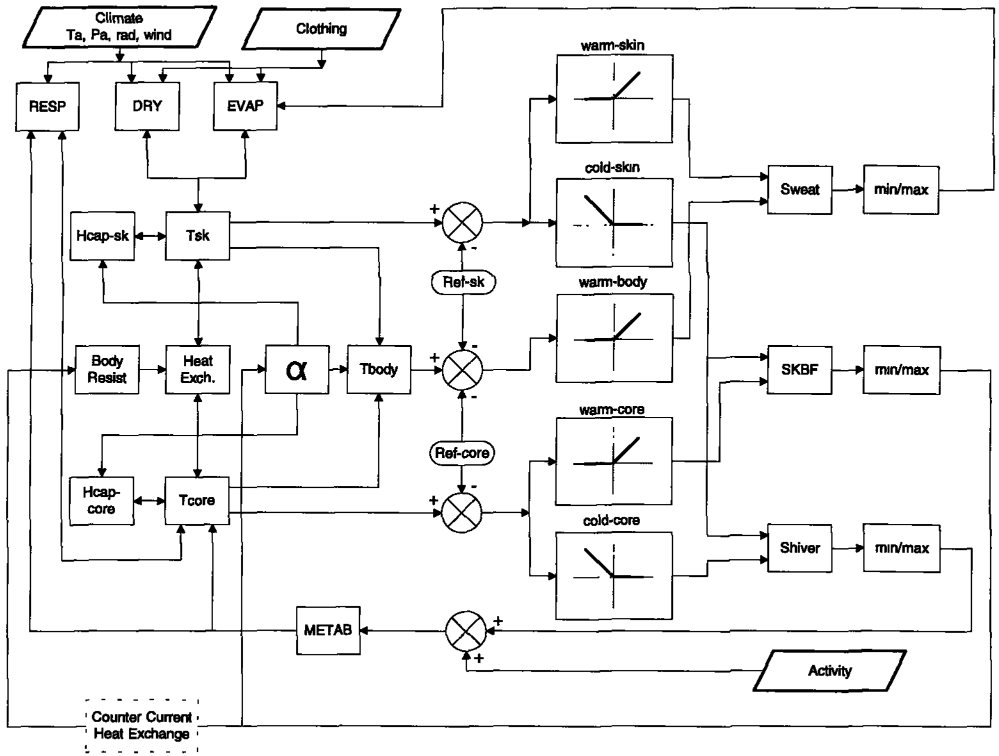

Fig. 2 Schematic representation of the physiological control system in the original computer model, the inputs (climate, clothing, activity) and the heat exchanges between body core and environment. The counter current heat exchange was not present in the original Gagge model, but was introduced by Lotens (1993). Abbreviations: Hcap = heat capacity; sw = sweating; sk = skin; BF = blood flow; SKBF = skin blood flow; Ref = reference temperature (setpoint); shiver= shivering metabolic rate; RESP = respiratory heat loss; DRY = dry heat loss (convection+radiation); EVAP = evaporative heat loss; α = relative size of skin compartment; others see text.

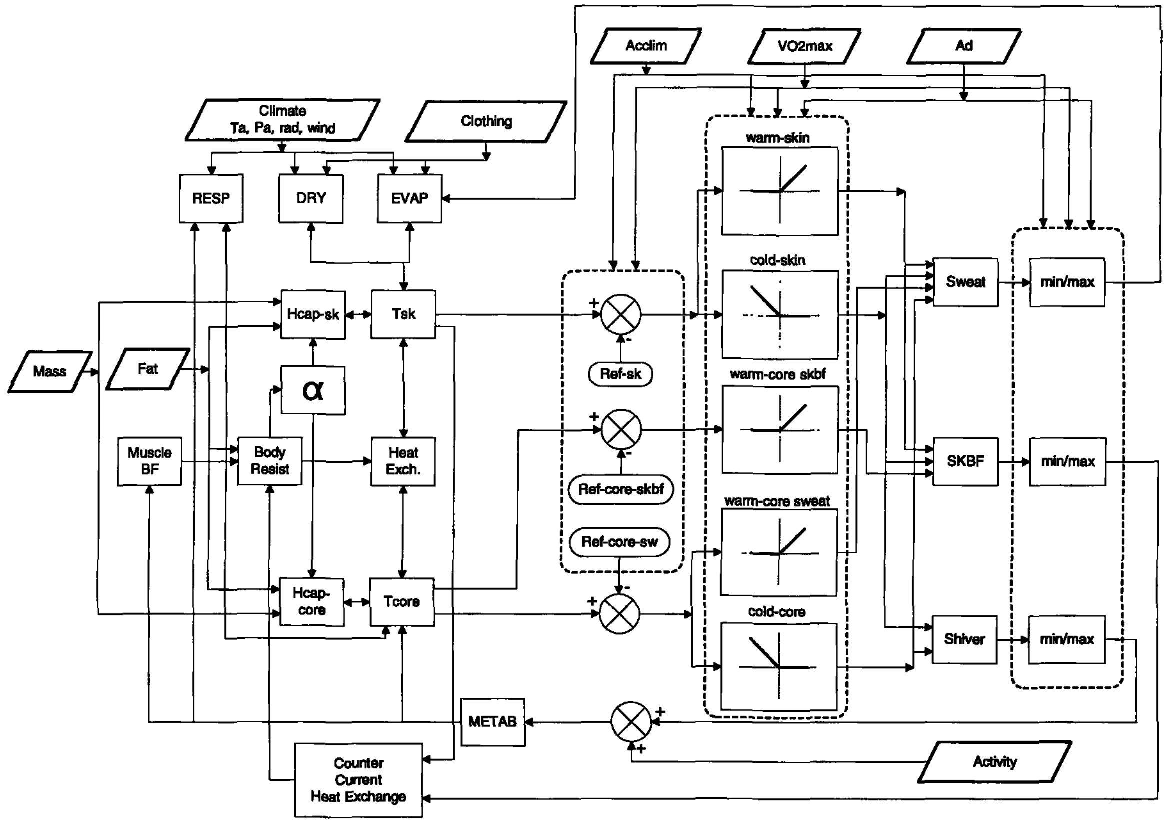

Fig. 3 Schematic representation of the physiological control system in the new computer model, the inputs (climate, clothing, activity, mass, fat content, acclimation, $\dot{V}O_{2\,max}$, A_D) and the heat exchanges between body core and environment. Abbreviations: Acclim = acclimation; Hcap = heat capacity; sw = sweating; sk = skin; BF = blood flow; SKBF = skin blood flow; Ref = reference temperature (setpoint); shiver= shivering metabolic rate; RESP = respiratory heat loss; DRY = dry heat loss (convection+radiation); EVAP = evaporative heat loss; α = relative size of skin compartment; others see text.

When performing simulations, the original model expects as inputs a time sequence of:

- the climatic parameters: temperature (T_a), humidity or vapour pressure (P_a), wind speed (v), and additional radiation between environment and skin (rad; e.g. fire or sun),
- the clothing parameters: heat and vapour resistance (I_{cl}, R_e), ventilation, and radiation properties,
- the persons activity level, expressed as the external work load and his metabolic rate (excluding the additional effect due to shivering which is generated by the model itself)

The main model output is the resultant body temperature (T_{co}, T_{sk}), or the total heat storage (STORE). Any other variables (skin blood flow, sweat rate etc.) can be requested as output too. The standard iteration interval used is 1 minute.

Considering the above mentioned input parameters, it is obvious that the model does not discriminate between different individuals when performing a simulation. It will produce the same output, based on parameter estimations on a group level, whether the subject is small or big, fit or unfit, acclimated or not. In reality, as discussed in chapter 1, individual differences may affect the control system as well as the passive system. Thus in order to improve the models performance on this point, changes and additions to the model were made.

6.3.2 The new model

General description

Starting with the inventory of inter-individual differences in heat stress response by Havenith (1985), and surveying recent literature on these subjects, several additions and changes to the governing equations in the model were made to "individualize" its response. The new model is schematically represented in Fig. 3.

The main change, compared to the original model, is obviously the increased number of input parameters. Apart from the input of climate, clothing and activity, the following features, fixed or absent in the old model, were added:

- body mass
- body fat layer thickness
- body surface area
- $\dot{V}O_{2\,max}$
- acclimation state

These can either be entered directly, or the model will help to deduce them from other, often more readily available parameters (A_D from mass and height; fat layer thickness from fat percentage, gender and age; acclimation state from number of acclimation days).

Apart from the input parameters, also some changes to the models structure were made, rationalizing parts of the model where physical or mathematical laws apply. These concern the composition of body core to skin heat resistance, introducing muscle resistance and fat resistance, changes in the calculation of the (variable) size of the core and skin compartments (α), and elimination of mean body temperature as separate parameter from the control functions.

The changes related to the individualization (schematically represented in Fig. 3), or the reason for not changing an item, will be discussed in detail in the following paragraphs.

Anthropometric characteristics and adiposity

The original model mimics a standard man (1.83 m, 75 kg, 15% fat). In order to enable the user to adjust the simulation to individual anthropometrics, an input option for the values for mass, height, and adiposity of the subject was added. The effects of these variables on body surface area, body heat capacity, and core-to-skin heat conductance were incorporated in the manner explained below.

Body surface area

Body surface area (A_D) is determined from body mass and height using the equation of DuBois and DuBois (1916). An effect of body surface area in general is the change in heat transfer area. As body surface area can vary substantially between subjects, this is an important effect to be incorporated in the model.

However, body surface area at a certain mass also varies with body fat content. When fat content increases at a fixed mass and height, it will replace heavier tissue types. Thus for the same mass, volume will increase and thus also surface area.

To estimate the magnitude of this effect, we calculated the effect of a large replacement of muscle mass, amounting 10% of body mass, with fat. The density of muscle tissue equals 1.1 $kg \cdot l^{-1}$, that of fat 0.9 $kg \cdot l^{-1}$ and that of tissue on average 1.077 $kg \cdot l^{-1}$ at 10% body fat content. Starting from the fat content of 10% (by weight), the volume is:

$$volume = \frac{75\ kg}{1.077\ kg \cdot l^{-1}} = 80.775\ l$$

The effect of a replacement of 10% of total body weight of muscle mass by fat mass can then be calculated as:

$$\textit{volume change for } 10\% \textit{ fat vs muscle} = \frac{-7.5\ kg\ muscle}{1.1\ kg{\cdot}l^{-1}} + \frac{7.5\ kg\ fat}{0.9\ kg{\cdot}l^{-1}}$$

$$= 1.5\ l \sim 1.9\%$$

The body surface area difference related to this 1.9% volume change is dependent of the location where this volume increase takes place. For the most extreme (hypothetical) case, when this volume would be added at the end of an extremity, the surface change would be about 3.5%. For the more likely case, when it would be added to the trunk it would be less than 0.5%. In view of these minor changes it seems overdone to add this effect of adiposity on A_D to the model.

With increasing A_D, also the area for sweat production will increase. For this reason, the amount of sweat produced by the body is made dependent of A_D, in a linear fashion, using the standard subject (75 kg, 1.83 m) with an A_D of 1.97 m^2 as a reference. The same approach has been chosen for skin blood flow (more skin area=more flow) and for maximal sweat production and blood flow:

$$\textit{sweat or blood flow} = \textit{controller output} \cdot \frac{A_D}{1.97}$$

$$\textit{maximal sweat production or blood flow} = \textit{standard maximum} \cdot \frac{A_D}{1.97}$$

Body heat capacity

Body heat capacity, relevant for determination of the magnitude of the body temperature change at a certain heat storage rate, is mainly determined by body mass. Further, the specific heat of body tissue is of importance. The latter is dependent on body composition. Specific heat of fat is lower than that of other tissues which are mainly water based (blood, muscle). The specific heat of body fat amounts to 2.51 $J{\cdot}g^{-1}$, whereas that of the other tissues (skin, skeleton, muscle etc combined) is on average 3.65 $J{\cdot}g^{-1}$ (Stolwijk, 1971, Burton and Edholm, 1955). For the calculation of body temperature changes the following equation for the specific heat of body tissue (c_b) is used:

$$c_b = \left(\frac{\textit{fat mass}}{\textit{body mass}}\right) \cdot 2.51 + \left(\frac{\textit{body mass} - \textit{fat mass}}{\textit{body mass}}\right) \cdot 3.65 \qquad (J{\cdot}g^{-1}{\cdot}{}^{\circ}C^{-1})$$

As the distribution of fat over skin and core compartment shows a strong variation between subjects, this specific heat value is taken equal for both segments

Core-to-skin heat conductance

The resistance to heat transport from the body core to the skin is formed by the body shell. This consists of muscle, fat and skin. The muscles are enclosed in the core segment, once they become well perfused as in exercise. When the shell is vasoconstricted, the heat flow from core to skin is mainly by conductance. When blood flow through these tissues increases, a convective component is added to the heat flow. In the original model, core-to-skin heat conductance is independent of adiposity and only dependent on thermally regulated skin blood flow:

$$\textit{Core-skin resistance} = \frac{1}{(5.28 + \textit{RAMAN} \cdot 1.163 \cdot \textit{Skin blood flow})} \quad (m^2 \cdot {}^\circ C \cdot W^{-1})$$

with: 5.28 = skin conductance in the absence of skin blood flow ($W \cdot m^{-2} \cdot {}^\circ C^{-1}$)
RAMAN = counter-current heat exchange effectivity
Skin blood flow = skin blood flow in $l \cdot m^{-2} \cdot h^{-1}$ (0.5 - 90)
1.163 = blood heat capacity in $J \cdot l^{-1} \cdot {}^\circ C^{-1}$ divided by 3600 $s \cdot h^{-1}$

This was deemed to be an over simplification in respect to the goal of this study.

Combining data from different sources (Pugh and Edholm, 1955; Nadel et al., 1974; Veicsteinas et al., 1982; Toner et al., 1986; Rennie, 1988), a general model for tissue conductance or resistance can be drawn as shown in Fig. 4. This model and the underlying data will be discussed in more detail below.

Most data on core-to-skin conductance were collected in water immersed subjects. Most studies used the concept of "critical water temperature"[5] for the determination of heat transfer properties of the body shell. This implies that in most of these studies, even with increased metabolic rate, skin blood flow will be minimal, or at least relatively low. Thus, it should be kept in mind that the numbers found for resistances of separate heat transfer pathways will pertain to situations with low skin blood perfusion, and will therefore represent mostly the resistances of muscle and fat. Values for these pathways can thus be successfully derived from the studies mentioned.

Literature data for the body shell insulation range from 0.32 $m^2 {}^\circ C W^{-1}$ for obese, resting subjects (water; Veicsteinas et al., 1982) to as low as 0.01 $m^2 {}^\circ C W^{-1}$ for lean, heavily exercising subjects (water; Nadel et al., 1974). Pugh and Edholm (1955) mention an average value for males of 0.093 $m^2 {}^\circ C W^{-1}$ and of 0.124 $m^2 {}^\circ C W^{-1}$ for females.

---

[5]Critical water temperature: The lowermost limit of water temperature in which insulative regulation of body temperature could occur without increased metabolic heat production.

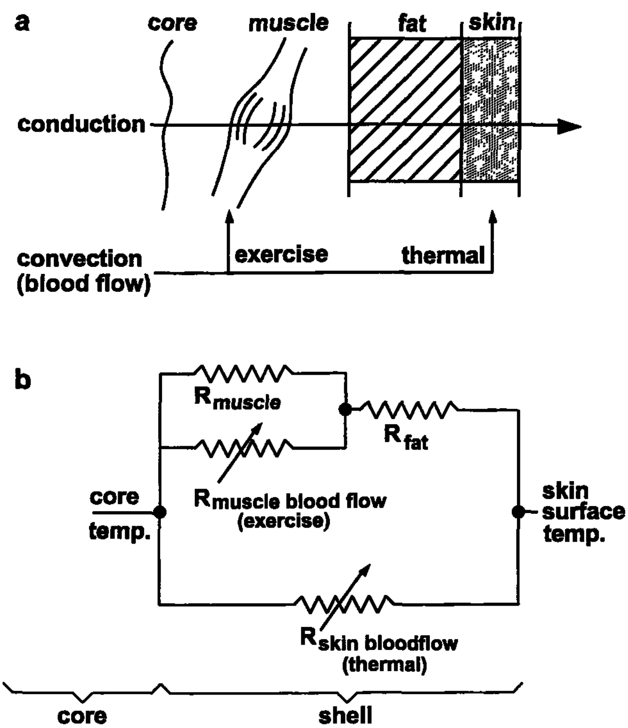

Fig.4 Schematic representation of the resistors involved in body core-to-skin heat transfer. Together with the core-to-skin temperature gradient these determine heat flow.

Fat layer: Individuals' shell insulation shows a good correlation with the subcutaneous fat thickness (Nadel et al., 1974; Veicsteinas et al., 1982; Rennie, 1988). Toner et al., (1986) also observed a relation between total body mass and shell conductance, with big subjects having a lower conductance. As their groups, though having equal fat percentages, differed apart from mass also in total skinfold thickness, the latter parameter may be the cause of the observed effect and not the actual mass.

Muscle layer: When vasoconstricted, the muscle layer forms a substantial part of the core-to-skin insulation (60-80%, measured in relatively lean subjects; Rennie, 1988). When a person becomes active, the perfusion of the working muscle increases strongly, and the muscle contribution to the shell insulation is extremely reduced (Rennie, 1988). Increases in work rates in respective experiments correlated well with reductions in shell insulation (Nadel et al., 1974; Veicsteinas et al., 1982; Rennie, 1988). At high activity levels (> 10 times basal metabolic rate), the shell insulation is between one fifth to one tenth of the maximal (0.05 $m^2 °CW^{-1}$) insulation value (Rennie, 1988).

In the old implementation of core to skin resistance in the model, as mentioned earlier, no relation with body composition was present. Also, metabolic rate had no direct effect on core to skin resistance. In the cold, muscle and skin blood flow are not necessarily related, however. From the literature described above a different representation can be developed following the representation of Fig. 4 with the following characteristics:

- *increasing work rate and metabolic* rate will increase core-to skin conductance through the increase in muscle blood flow. Since this blood flow is mainly axial (extremities), there is a correlation with radial heat flow, rather then an actual radial convective heat transport.
- skin blood flow in itself will affect core-to-skin conductance through its convective heat transport, which shortcuts the tissue conductive resistances. This was already present in the model.
- the subcutaneous fat layer thickness represents a constant conductive heat resistance.

These points are incorporated in the new representation of core-to-skin conductance in the model using the data from the given literature, with an emphasis on the paper by Rennie et al., (1988). The essentials of the new description are (Fig. 4):

$$R_{core\ to\ skin} = \frac{1}{\left(\frac{1}{R_{skin\ blood\ flow}} + \frac{1}{R_{muscle+fat+skin}}\right)} \qquad (m^{2} \cdot {}^{\circ}C \cdot W^{-1})$$

with:

$$R_{muscle+fat+skin} = R_{fat+skin} + \frac{1}{\left(\frac{1}{R_{muscle,\ conductive}} + \frac{1}{R_{muscle\ blood\ flow}}\right)} \qquad (m^{2} \cdot {}^{\circ}C \cdot W^{-1})$$

As muscle blood flow as such is not defined in the model, but this evidently is related to metabolic rate, this factor can be represented as a function of metabolic rate. Skin blood flow is already a parameter in the model, incorporated as a function of body temperature. The other parameters were deducted from the data in the mentioned papers, with the assumption that due to the experimentation in water at critical water temperature, the tissue insulation was maximal and skin blood flow, even during exercise, was minimal. The equations for the three components of core to skin resistance put into the model then read:

$$R_{skin\ blood\ flow} = \frac{1}{(1.167 \cdot RAMAN \cdot Skin\ blood\ flow)} \qquad (m^2 \cdot {}^\circ C \cdot W^{-1})$$

$$R_{muscle} = \frac{0.05}{1 + \left(\frac{metabolic\ rate - 65.}{130}\right)} \qquad (m^2 \cdot {}^\circ C \cdot W^{-1})$$

$$R_{fat+skin} = 0.018 \cdot Thickness_{fat+skin\ layer} \qquad (m^{2} \cdot {}^\circ C \cdot W^{-1})$$

The thickness of skin and fat is readily available to model users when they apply the common method of measuring skinfold thicknesses (preferably an average of > 5 sites) for adiposity assessment.

$$Thickness_{fat+skin\ layer} = 0.5 \cdot mean\ skinfold\ thickness \qquad (mm)$$

If the skinfold thickness is not available, but instead only the body fat percentage is known, the mean skinfold thickness has to be derived from this. Body fat percentage, as measured by under water weighing, would imply conversion problems since Davies et al., (1986) showed that a wide variation exists between subjects in the distribution of total body fat over the subcutaneous fat layer and the internal fat compartments.

Jackson and Pollock (1985) gave relations between % body fat, body density and skinfold thickness (seven point average):

$$Body\ Fat = \left[\frac{4.95}{D_{body}} - 4.50\right] \cdot 100. \qquad (\%)$$

$$D_{body,\ male} = 1.112 - 10^{-6} \cdot (434.99 \cdot SF + 0.55 \cdot SF^2 - 288.26 \cdot age) \qquad (kg \cdot l^{-1})$$

$$D_{body,\ female} = 1.097 - 10^{-6} \cdot (469.71 \cdot SF + 0.56 \cdot SF^2 - 128.28 \cdot age) \qquad (kg \cdot l^{-1})$$

with:

D_{body} = average density of body tissue
SF=sum of seven skinfolds,

These equations can be used in an inverse way to retrieve skinfold thickness from %

body fat.
For the model, using gender, age and the body fat percentage as input, the sum of seven skinfolds (SF) was derived with these equations, and from this SF, the average superficial fat+skin layer thickness was calculated:

Gender and age

The gender and the age of the subjects will not be introduced in the model as factors directly affecting thermoregulation. Enough evidence is present in literature (for a discussion see Havenith, 1985; Havenith et al., 1990, 1995a) showing that the main influence of age and gender in exercise heat exposure really acts through concomitant differences in aerobic power, fat content, mass and A_D. Optionally, the user may be given the choice to select gender and age for an individual subject, but in the model this would be translated in a change in aerobic power, fat content, mass etc. based on epidemiological data of differences in these parameters between genders and ages.

Sweating control

Individual differences in sweat production can be quite large. This is in part related to large differences in sweat gland size (1.35 - 7.3 · 10^{-3} mm^3; Sato and Sato, 1983), number and distribution and in sweat production per gland (Hertzman, 1957, Kuno, 1956). When heat stress increases, total sweat output differences are reduced, however (Hertzman, 1973). For the modelling of individual differences in sweat output, major parameters are the training level of the subject (Henane et al., 1977, Nadel et al., 1974, Gisolfi, 1984) as well as by the level of acclimatization (Avellini and Kamon, 1980, Candas et al., 1980, Candas 1980, Davies, 1981, Kobayashi et al., 1980, Mitchell et al., 1976). Most textbooks follow the relations between training, acclimation and sweat rate as presented by Nadel et al., (1974). They suggest that the relationship between sweat rate and core temperature is linear above the sweat threshold (at constant T_{sk}), and that training increases the gain of this relationship and acclimation decreases the core temperature threshold value. The simplicity of this theory is appealing, but there are two points which justify closer scrutiny of its basis. The presented "typical" graphs always are from single subjects, and responses from different individuals within a group were often inconsistent. Also, the relations are obtained during rapid warming within 10-20 min. A possible time constant of the system, or time lag between the measured esophageal and the actual "core" temperature would have a strong impact on the observed relation (Havenith, 1985). Therefore we chose to reevaluate the literature on the subject of training and acclimation effects on the sweat rate-T_{co} relation. An overview of the findings from which also quantitative data could be obtained is presented in Table 1.

Table 1 Overview of data relating to the effect of training and acclimation on the sweat rate-T_{co} relation. *Data of Roberts et al., (1977) are recalculated with exclusion of an apparent outlier.

source	n	condition	change in T_{co} rest (°C)	$\dot{V}O_{2\,max}$ subjects ($ml \cdot kg^{-1} \cdot min^{-1}$)	change in $\dot{V}O_{2\,max}$	sweat threshold (°C)	sweat gain	max. sweat rate ($g \cdot h^{-1}$)
Henane + Bittel 1975	12	rest + heat	-0.2	?		↓-0.27	↑ (in 50% subjects)	
Wyndham, 1967	13 /353	exercise + heat		apprentice miners versus miners		↓-0.5 (between groups)		520→800 (+54%)
Kobayashi, 1980						↓		
Nadel et al., 1974	6	exercise training ($75\%\dot{V}O_{2\,max}$)		38.1 → 44.7	+17%	↓-0.1	+67%	
		heat		?	0?	↓-0.2	+0%	
		exercise ($50\%\dot{V}O_{2\,max}$)+ heat		?	+17%?	↓-0.3	+67%	
Henane + Valatx, 1973	9	rest + heat				↓	=	
Henane et al., 1977	3	exercise (25/110%$\dot{V}O_{2\,max}$ cycles)	-0.4	40.9 → 48.3	+18%	↓-0.1 --0.4	+60%	
Shvartz 1979	10	exercise ($50\%\dot{V}O_{2\,max}$) + heat		41	n.s.	↓-0.49		
Gonzalez, 1974	6	low exercise ($25\%\dot{V}O_{2\,max}$)+ heat		50.3	n.s.	↓-0.5	+47%	
Roberts et al., 1977*	8	exercise training ($75\%\dot{V}O_{2\,max}$)		42.7 → 47.7	+12%	↓-0.1	+36%	
		heat only		47.7 →46.9	-1.7%	↓-0.12	+14%	
		exercise ($50\%\dot{V}O_{2\,max}$) + heat		42.7 →46.9	+10%	↓-0.22	+54%	
Heany, 1994	10	heat + low exercise ($33\%\dot{V}O_{2\,max}$)		48	n.s.			+25% (at lower T_{co})
Havenith and van Middendorp, 1986	4	heat+low exercise (constant strain)		54	n.s.	↓-0.25	=	

The presented sweating threshold values are defined as values at which sweat evaporation was found to increase. This is in contrast to some literature, which report extrapolated thresholds. They extrapolate the sweat rate-T_{co} relation back to the point of zero central drive as suggested by Nadel et al., (1974). The latter threshold is the point where the gland is supposed to be activated. The difference between the two definitions is the amount of sweat which has to be produced before it actually reaches the skin surface and evaporates. In the duct, part of the sweat is absorbed. If the zero central drive definition would have to be used for modelling, knowledge of the amount of sweating needed for appearance of sweat at the skin surface would be necessary (sweat duct volume, sweat duct resorption). Insufficient data are yet available for that purpose.

Training versus acclimation

Several studies have separated the actual training effect from that of heat acclimation alone or the combination of heat and training. Comparison of quantitative effects is difficult, as the size of effects is strongly related to the methods used. For the achievement of significant training effects on thermoregulation e.g., exercise intensities above 50%$\dot{V}O_{2\,max}$ are needed (Pandolf 1979). In many experiments these were not always warranted (Shvartz et al., 1973; Strydom and Williams, 1969). Starting with exercise intensities at a constant load above this level, the increasing aerobic power levels in the course of the experiment due to the training result in a continuous decrease in relative load for the subject. This often resulted in relative loads below 50% $\dot{V}O_{2\,max}$.

A problem with the interpretation of data for the "maximal sweat rate" is that usually heat stress tests before and after the treatment (i.e. acclimation) were identical, and thus the treatment may have resulted in a reduced strain in the second test. Thus though equal or even lower sweat rates may be observed after treatment, actual maximal sweat capacity may have increased.

Considering the results summarized in Table 1, it seems that heat, exercise and the combination of heat and exercise all have an effect on the threshold for sweat appearance at the skin surface. Threshold shifts due to exercise training alone (changes in $\dot{V}O_{2\,max}$ of 12 to 17%) range between 0.1 and 0.4°C, but considering the numbers of subjects used in different studies, a shift of 0.1 °C seems the best consensus. Heat acclimation following exercise training (Nadel et al., 1974, Roberts et al., 1977) produces an additional setpoint shift of 0.12 to 0.2°C. The total threshold reduction of heat + training amounts to 0.22 to 0.5°C. Threshold shifts due to heat acclimation alone are only available from Henane and Bittel (1975) and amount 0.27°C. Low exercise during heat acclimation results in a shift of approximately 0.25 to 0.5°C (Gonzalez, 1974, Havenith and van Middendorp, 1986), which is not substantially less then heat+high exercise. In general, the main shift in threshold seems to be caused by the heat exposure.

With respect to the change in gain of the sweat rate-T_{co} relation, observations (Table 1) range from 36 to 67% increase for exercise training, from 0 to 14% for a subsequent heat with exercise regime and from 54 to 67% for the total of heat + exercise training acclimation. Heat alone (Henane and Bittel, 1975) results in increased gain in part of the subjects, but an average number could not be obtained from the data. Heat + low exercise (Gonzalez, 1974, Havenith and van Middendorp, 1986), results in 0 to 47% gain increase. Thus training seems the major factor in the gain increase, but heat by itself also has an effect.

The aerobic power level of the subjects used in the training experiments of Table 1 ranged between 38.1 and 42.7 $ml \cdot kg^{-1} \cdot min^{-1}$ before training. Compared to a normative reference (Morrow et al., 1995), these subjects can be characterized as below average to average. The level increased after training to average/above average. Over all experiments, the starting aerobic power level of all subjects ranged from below average to good. When considering the studied effects over a larger population, one may expect a wider distribution in aerobic power levels, and thus the differences in associated thermoregulatory responses are likely to be larger than observed here.

For modelling purposes, training and acclimation need an operational definition, which will be considered below:

No quantitative data are available on the effect of humid versus dry heat acclimatization on thresholds and gains of the sweat system. Several reports have shown that acclimatization to one type of climate is also beneficial for the other (Bean and Eichna, 1943, Eichna et al., 1945, Griefahn, 1994, Griefahn et al., 1992). For the model, no distinction between dry and humid heat acclimation will be made.
Further, no quantitative data are available on the differences between acclimation to different stress levels (e.g. 30°C and 40°C). The higher the acclimatization load, the higher the expected change in thermoregulatory stability is expected to be. However, as at present this cannot be quantified, it was chosen to operationalize acclimatization in the model as a simple parameter: the number of acclimation days (exposures to a stressful climate (WBGT > 30°C) which increased body core temperature substantially) without further distinction between climate type and heat load level. The shape of the relation (acclimation effect versus number of acclimation days) was adapted from Givoni and Goldman (1973), and Neale et al., (1996):

$$acclimatisation = 1 - e^{-0.3 \cdot \text{number of acclimation days}}$$

The magnitude of the pure acclimation effect, separated from the training effect was derived from the data discussed above.

For a training effect on the regulation characteristics of sweating and skin blood flow to be present, an actual increase in $\dot{V}O_{2\,max}$ has to be observed. Thus the absolute value of $\dot{V}O_{2\,max}$ by itself (a sum of genetic and training influences) does not have to be a valid parameter for the "acclimation like" effects of exercise training. However, a strong correlation of $\dot{V}O_{2\,max}$ with heat tolerance has been observed (Pandolf, 1977, 1979) and it seems fair to use $\dot{V}O_{2\,max}$ (expressed in $ml \cdot kg^{-1} \cdot min^{-1}$ for separation from the mass effect) as indicator for training and aerobic power induced effects on the sweat rate-T_{co} relation.

As mentioned above, the effects described in Table 1 are for a limited $\dot{V}O_{2\,max}$ range. Thus the model will use this range as a scaling factor for changes outside this range of $\dot{V}O_{2\,max}$ values. In absence of data on the relation between the range of $\dot{V}O_{2\,max}$ and observed effects, the scaling factor is chosen as linear.

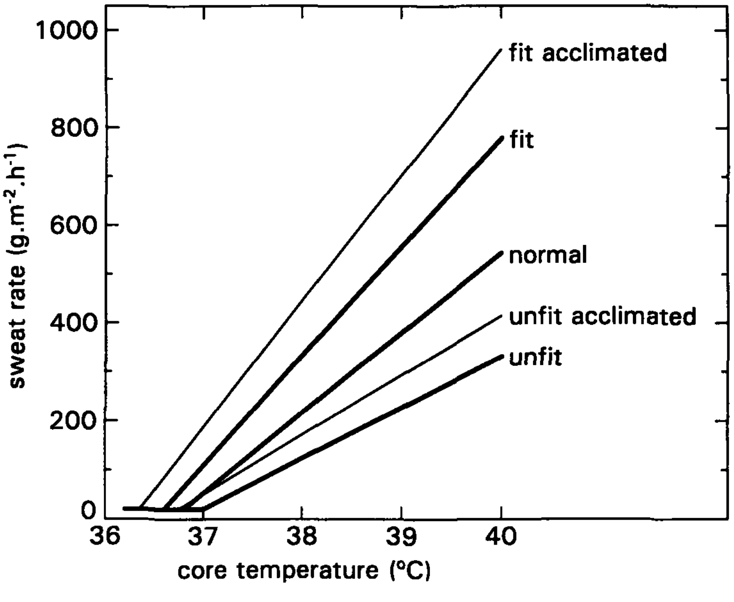

Fig. 5 Graphical representation of the influence of aerobic power and acclimation on the control function for sweating, assuming a constant skin temperature.

The practical implementation of the effects of aerobic power and heat acclimation on the model's sweat control function is illustrated in Fig. 5, and can be described as follows: The factor training was implemented as being defined in terms of a range in $\dot{V}O_{2\,max}$, expressed in ml·kg^{-1}·min^{-1}. This can be entered directly, or as derived from absolute $\dot{V}O_{2\,max}$ (l·min^{-1}). The range used for having an effect on the sweat rate-T_{co} relation is arbitrarily chosen to be 20-60 ml·kg^{-1}·min^{-1}. This covers the fitness ranges 'very poor' to 'good' for young and old subjects (Morrow et al., 1995). For the setpoint shift related to $\dot{V}O_{2\,max}$, from Table 1 a number of 0.1 °C was derived for a 10 ml·kg^{-1}·min^{-1} range, which for the full range (40 ml·kg^{-1}·min^{-1}) is extended to 0.4 °C. For the gain change, the increase seen in Table 1 of 36-67% for the 10 ml·kg^{-1}·min^{-1} range was extended to 200% for the full range (unfit to fit). Taking the aerobic power average of 40 ml·kg^{-1}·min^{-1} as a reference (18-45 year average; Morrow et al., 1995) this leads to the following training and acclimation based adjustments in the governing equations, which modify setpoint and gain:

$$fit = VO_{2\,max} - 40 \qquad (ml \cdot kg^{-1} \cdot min^{-1};\ 20 \leq VO_{2\,max}/kg \leq 60)$$

$$acclim = 1 - e^{-0.3 \cdot number\ of\ acclimatisation\ days} \qquad (0 \leq number\ of\ accl.\ days \leq 14)$$

$$setpointnew = setpoint - \left(\frac{fit}{10}\right) \cdot 0.1 - acclim \cdot 0.25 \qquad (°C)$$

$$gainnew = gain \cdot \left[1 + \frac{fit}{20} \cdot 0.35\right] \cdot [1 + acclim \cdot 0.15] \qquad (g \cdot m^{-2} \cdot h^{-1} \cdot °C^{-1})$$

For maximal sweat rate (MSR), a difference of 100% between unfit, unacclimatized, and fit, acclimatized was arbitrarily chosen, mainly based on data from metacholine injection studies (Inoue et al., 1997) and studies comparing medium fit unacclimatized subjects with fit acclimatized (Wyndham, 1967, Table 1).

$$MSR_{40} = maximum\ for\ unacclimatized\ 40\ ml \cdot kg^{-1} \cdot min^{-1}\ person$$

$$MSR = MSR_{40} \cdot \left[1 + \left(\frac{fit}{20}\right) \cdot 0.25 + acclim \cdot 0.25\right] \qquad (g \cdot m^{-2} \cdot h^{-1})$$

Skin blood flow

The regulation of skin blood flow has been studied through skin blood flow in the extremities (plethysmographic techniques) and through core-to-skin conductivity. Extremity blood flow is regarded as indicative/representative for total body skin blood flow, and provides a more direct measure than core-to-skin conductivity does.
Data on the effect of training and acclimation on skin blood flow are limited, and often conflicting. Acclimation results in a reduced core temperature threshold for forearm, hand, chest and ear vasodilation (Fox et al., 1963; Roberts et al., 1977; Gonzalez et al., 1974). Also maximal conductance measured at the chest increases (Gonzalez et al., 1974). Besides increased vasodilation (Wood and Bass, 1960), also venoconstrictor tone increases in the first days of acclimation. Comparisons before and after acclimation do not show changes in skin blood flow, however. This may be due to reduced strain after acclimation, reducing the necessity of high blood flows at equal stress. Also, venous tone is strongly affected by non-thermal influences.
Wyndham (1951), studied the effect of acclimation (with exercise) during extreme heat exposure. With this maximal stimulus, forearm blood flow increased from 14 to 26 $ml{\cdot}100ml^{-1}{\cdot}min^{-1}$. Roberts et al., (1977) provided quantitative data on setpoint and gain of the forearm blood flow - T_{co} relation. They observed a significant reduction in threshold for vasodilation of 0.2°C by exercise training ($\dot{V}o_{2\,max}$/kg: 42.7 -> 47.7 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) and another reduction by 0.26°C by successive exercise+heat acclimation. The change in gain was less consistent. Exercise training resulted in an average gain increase of 1.3 $ml{\cdot}100ml^{-1}{\cdot}min^{-1}{\circ}C^{-1}$ and subsequent acclimation by heat and exercise in a reduction with 0.8 $ml{\cdot}100ml^{-1}{\cdot}min^{-1}{\circ}C^{-1}$. However, the validity of these gain changes for a generalized model is questionable, as different subjects showed very different reactions (4 out of 6 subjects showed the gain increase with training, 2 a decrease; 6 out of 8 the decrease with heat acclimation against 2 with an increase and the total of training with subsequent acclimation showed only 2 out of 6 with an increase and 4 with a decreased gain).

The maximal value of skin blood flow in relation to aerobic power has received little attention in literature. As during heat stress, a competition exists between blood flow for supply of nutrients and oxygen to muscles and skin blood flow for core-to-skin heat transport, it is likely that a high maximal cardiac output is a good indicator for the ability to produce and maintain a high skin blood flow. Maximal cardiac output is strongly related to $\dot{V}o_{2\,max}$ (Ekblom, 1969 in Åstrand and Rodahl 1970). Thus it seems reasonable to relate maximal skin blood flow in the model to the parameter for aerobic power. Acclimation will have an effect on maximal skin blood flow due to its stabilizing effect on circulation. The size of this effect is supposed to be smaller than that of aerobic power, however.

In the original model the basal skin blood flow rate is 6.3 $l{\cdot}m^{-2}{\cdot}h^{-1}$ with a maximum of 90 $l \cdot m^{-2} \cdot h^{-1}$. Skin blood flows measured with plethysmographic techniques are around 1 $ml \cdot 100ml^{-1} \cdot min^{-1}$ at rest and on average 15 $ml \cdot 100ml^{-1} \cdot min^{-1}$ at maximum. This is the same ratio. The maximal skin blood flow between subjects of different aerobic power levels usually ranges between 10 and 20 $ml \cdot 100ml^{-1} \cdot min^{-1}$ (Havenith, 1995). Thus, translated to model units the maximum should range from 60 to 120 $l \cdot m^{-2} \cdot h^{-1}$ for different aerobic power levels, with a mean of 90 $l \cdot m^{-2} \cdot h^{-1}$ at an average aerobic power.

For the model, equations graphically represented in Fig. 6 were used:
For the setpoint shift, considering the limited amount of data, an analogy with the setpoint shift due to training for sweating was chosen. Again, a person with a $\dot{V}O_{2\,max}$/kg of 40 $ml \cdot min^{-1} \cdot kg^{-1}$ was taken as reference. For acclimation a shift of 0.25 was taken.

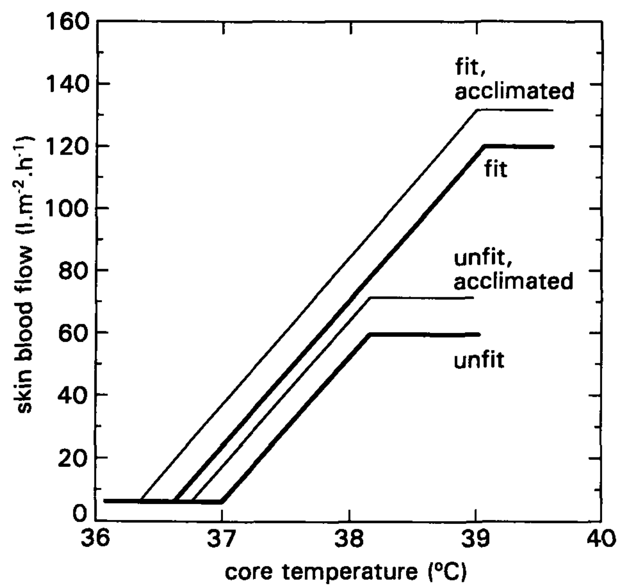

Fig. 6 Graphical representation of the influence of aerobic power level and acclimation on the control function for skin blood flow, assuming a constant skin temperature.

$$fit = VO_{2\,max} - 40 \qquad (ml \cdot kg^{-1} \cdot min^{-1};\ 20 \leq VO_{2\,max}/kg \leq 60)$$

$$acclim = 1 - e^{-0.3 \cdot number\ of\ acclimatisation\ days} \qquad (0 \leq number\ of\ accl.\ days \leq 14)$$

$$setpoint\ new = setpoint - \left(\frac{fit}{10}\right) \cdot 0.1 - acclim \cdot 0.25 \qquad (°C)$$

For the gain, no effect was introduced due to the inconsistency in the data.
For maximal skin blood flow (MSBF) the effects of aerobic power and acclimation were formulated as follows:

$$MSBF_{40} = maximum\ for\ unacclimatized\ 40\ ml \cdot kg^{-1} \cdot min^{-1}\ person$$

$$MSBF = MSBF_{40} \cdot \left[1 + \left(\frac{fit}{60}\right) + acclim \cdot 0.15\right] \qquad (ml \cdot 100\ ml^{-1} \cdot min^{-1})$$

Mean body temperature calculation

In the model 2 nodes are treated separately: core and skin. The core compartment is defined as having a regulated, uniform temperature which is defended against external influences. The shell is used as an intermediate layer between core and environment, which temperature is less uniform, and which temperature defence is subordinate to that of the core. The size of these nodes is not constant. When a subject is highly vasoconstricted, perfusion of the skin and the extremities will be minimal. The body shell will cool down and become relatively larger in size than in a vasodilated state. For calculations of body heat content, mean body temperature, or changes in node temperature with a certain heat influx, the current model uses a parameter α to present the relative contribution of the shell (skin) node to the total body:

$$T_{body} = (1 - \alpha) \cdot T_{re} + \alpha \cdot T_{sk} \qquad (°C)$$

The size of α is in the original model dependent on skin blood flow:

$$\alpha = 0.042 + \frac{0.745}{(skin\ blood\ flow + 0.59)} \qquad (skin\ blood\ flow\ in\ l \cdot m^{-2} \cdot h^{-1})$$

The value of α in neutral to hot conditions varies in simulations between 0.15 to 0.05.

These values are very low, compared to literature, as can be seen in Fig.7. In this figure, the relative size of the core compartment (1-α) is presented, since that is more common in literature. The low α in the model also has consequences for the model's behaviour. If e.g. condensation on the skin takes place, T_{sk} rises disproportionally due to the liberation of the heat of condensation in a very thin skin layer. One reason behind the calculation resulting in these low α values in the original model may be that α not only determines the weighing of skin versus core for the body heat content calculation, but it also determines the weighing for the sensitivity of sweating and skin blood flow to temperature changes in the skin versus changes in the core compartment. Most literature actually suggests a sensitivity for skin temperature less than one tenth of that of core temperature (Stolwijk, 1971; Stolwijk and Hardy, 1977), suggesting α values below 0.1.

For the model, these two meanings of α will be separated into a fixed sensitivity for core versus skin and a variable α value for the determination of the shell size. The data in Fig.7 suggest that the minimal value for α should be 0.1, and the total range from cold to hot should be 0.35 and 0.1 respectively.

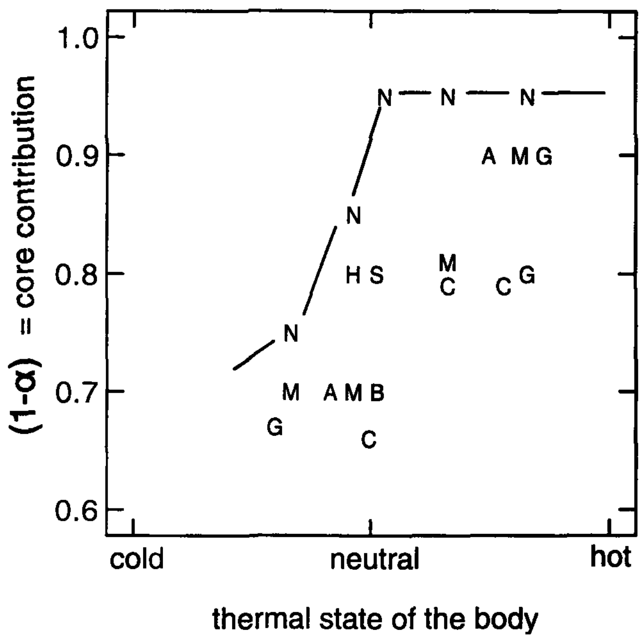

Fig. 7 Proposed values for the relative size of the core compartment (1-α) from different sources are presented, including the α values for the original model (line). N=Gagge et al., 1986; G=Gagge and Nishi, 1977; B=Burton and Edholm, 1955; H=Hardy and DuBois, 1938; S=Stolwijk and Hardy, 1966; C=Colin et al., 1971, A=ASHRAE, M=Malchaire, 1996.

As α is dependent on the actual core-to-skin resistance and as the effect of adiposity and muscle blood flow on core-to-skin resistance are now incorporated in the model, it seems logical to have α incorporated in the model as a function of total core-to-skin resistance. Based on the data of Fig. 7, the following equation provides a good representation of the α - T_{co} relation:

$$\alpha = 0.08 + 2. \cdot Resistance_{core-skin} \qquad (0.1 < \alpha < 0.35)$$

The effect of using this equation is presented in Fig. 8. There 1-α is shown in relation to T_{re} for both the original and the new model, assuming a constant skin temperature of 34 °C. The latter causes the limitation of 1-α to ± 0.75, as a lower 1- α will only be achieved at lower skin temperatures. The change between the old and the new model is a combined effect of the new representation of α itself and the effect of the changed control curve for skin blood flow on the α-T_{re} relation.

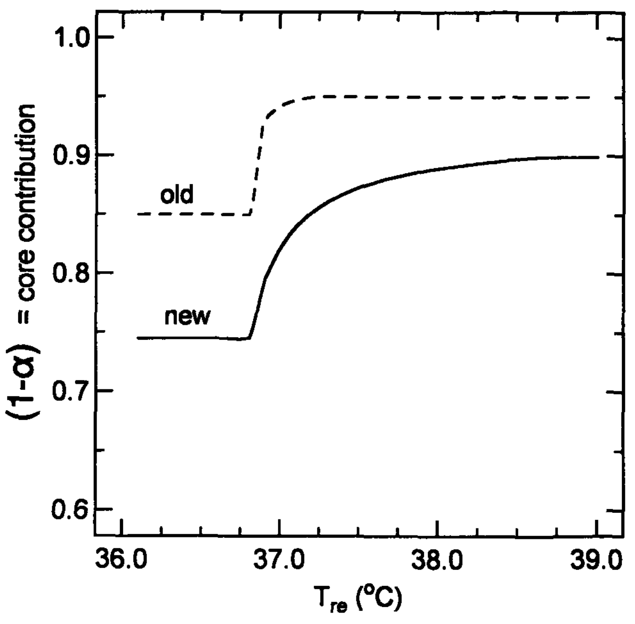

Fig. 8 Effect of altered representation of the core and skin compartment contributions (1-α, and α) to the total body compartment on the relation between T_{co} and α, assuming a constant skin temperature. Old= original model, new= present model.

6.4 Validation

6.4.1 Methods

With all the listed changes incorporated in the model, the question needs to be answered whether the changes actually lead to an improvement of the prediction results. For this purpose, both the original and the new model's predictions for individual heat stress responses were evaluated, using data sets which have not been used in the design of the new model, and which are therefore truly independent.

The validation was performed using data for rectal and skin temperature and for body heat storage obtained by Havenith et al., (1990, 1995a,b, 1996) in a cool (CO; 20°C, 50%), warm humid (WH; 35°C, 80%) and a hot dry (HD; 45°C, 20%) climate, exercising either at fixed workloads (ABS; 60 Watt) or loads relative (REL, 25/45%)) to the individual maximum $\dot{V}O_2$.

For the original model, having no individual input parameters, only one simulation run was needed for each climatic condition, using the average metabolic rate and work load derived from the data sets. This results in the same output values per condition for all subjects. For the new model, for each subject and condition, a separate simulation run with the actual data for climate, work load, metabolic rate, $\dot{V}O_{2\,max}$, body mass, body fat content, height, and acclimatization status was performed.

Acclimatization was set to zero for all subjects, and was thus not a part of this evaluation. The approach used for heat acclimatization/acclimation in the current model has been evaluated before by Neale et al., (1996), with good results.

The validation of the new model with the data sets mentioned resulted in 181 simulation runs. The final values for body core temperature, skin temperature and body heat storage were subsequently used for evaluation of the model's performance. This performance will be discussed for the new versus the original model, for the new model on its own (the individualization), and for the new model versus the regression model presented in previous chapters.

Parameters used for the quantitative validation are:

- the mean and the standard deviation of the difference between computed and real output values,
- the correlation between the computed and the real output values,
- the differences in explained variance (r^2) between simulation and regression model.

6.4.2 Validation Results

New versus old model

In Table 2, the performance of the original model (Lotens, 1993) versus that of the new model is illustrated based on the mean values for the prediction error of the models (computed minus measured value) for each condition and on the standard deviation of that error. These numbers in Table 2 clearly show two effects of the new model compared to the old one: the mean error is smaller for the new model (all T_{re} and T_{sk} predictions; three out of five storage conditions), and so is the standard deviation (except one T_{re} and one T_{sk} condition). Thus the average systematic under- or overestimation by the model is smaller for the new model, and the distribution of the error values is narrower around their mean. This is supported by the mean errors and their SD values over all conditions combined. From this we can conclude that the performance of the new model has improved compared to the original model. Quite a substantial error remains, however.

Individualization (new model)

Though the performance of the new model has improved compared to the old one, this improvement is not necessarily due to individualization. The mean error may have been improved due to a lower systematic error alone, without actually improving the prediction of an individual's deviation from the group mean. The latter can be studied by looking at the correlation between computed and measured points. If the computed values and the real data both are on the same side of the respective group mean (thus both discriminating more versus less heat tolerant subjects), one expects a correlation between computed and real data within each condition to be present. The correlations between computed and real data values are presented in Table 2 (for the old model, these are 0, due to the lack of variance within each condition). This Table shows that the individual predictive value for the model varies strongly between conditions. Calculating as an example the explained variance for body heat storage from the presented numbers (r^2) this explained variance amounts 77% taken over all conditions, but the explained variance due to the individualization of the model varies between 4% (condition CO/REL) and 53% (WH/REL) over conditions. Thus for several conditions (CO/REL and HD/REL) the models predictive capacity for effects of individual differences is low (<10%), and for others (WH/REL, WH/ABS, HD/ABS) it is significant (27-53%).

Table 2 Mean value and standard deviation (S.D.) of the differences between the results of the model simulation and the original data for both the original and the new model. For the new model, also the correlation coefficients (*r*) of the relation between simulated and real physiological responses are shown. Due to the missing variance in the model predictions for the old model the *r* value is always zero in that case.

response	condition	number of cases	original model mean error ± SD	new model mean error ± SD	new model *r*
T_{re}			°C	°C	
	CO/REL	24	-0.53 ± 0.29	-0.23 ± 0.32	-0.09
	WH/REL	24	0.29 ± 0.23	0.24 ± 0.19	0.67
	HD/REL	24	0.46 ± 0.36	0.33 ± 0.36	0.24
	WH/ABS	80	-0.60 ± 0.37	-0.29 ± 0.30	0.57
	HD/ABS	29	-0.04 ± 0.48	-0.00 ± 0.38	0.65
	overall	181	-0.21 ± 0.55	-0.07 ± 0.40	0.63
T_{sk}			°C	°C	
	CO/REL	24	3.81 ± 1.00	2.28 ± 0.95	0.47
	WH/REL	24	-0.45 ± 0.34	0.44 ± 0.28	0.73
	HD/REL	24	-1.63 ± 0.70	-0.93 ± 0.65	0.33
	WH/ABS	80	-0.81 ± 0.37	-0.24 ± 0.44	0.04
	HD/ABS	29	-2.32 ± 0.80	-1.69 ± 0.77	0.26
	overall	181	-0.45 ± 1.98	-0.12 ± 1.34	0.95
body heat storage			$J \cdot g^{-1}$	$J \cdot g^{-1}$	
	CO/REL	24	1.19 ± 1.04	0.95 ± 1.12	0.19
	WH/REL	24	0.48 ± 0.77	0.99 ± 0.65	0.73
	HD/REL	24	0.15 ± 1.24	0.26 ± 1.21	0.26
	WH/ABS	80	-2.23 ± 1.11	-0.98 ± 1.02	0.52
	HD/ABS	29	-1.72 ± 1.75	-1.19 ± 1.36	0.64
	overall	181	-0.90 ± 1.83	-0.26 ± 1.42	0.88

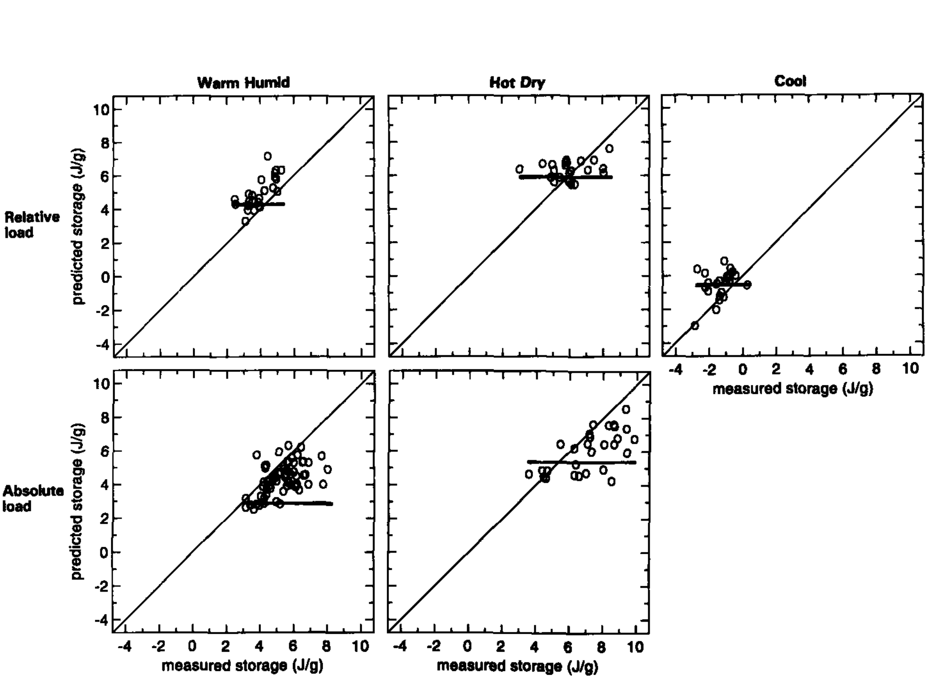

Fig. 9 relation between predicted and real body heat storage (J·g^{-1} body mass) for the separate conditions of the experiments. Circles= new model computations, horizontal line = range of datapoints for the old model computation (as the predicted value is equal for all subjects, and the measured values do vary, all points project on this line).

As an illustration, the relations between computed and real measurements are presented for body heat storage in Fig. 9. As already shown in 4.2.1, also this graph, shows that the model does not always predict around the line of identity. In some conditions the calculations systematically overestimate heat storage, in others it underestimates it.

New model versus empirical regression model

In the papers, in which the used data were described, the data were analysed for the influence of individual characteristics on the heat stress response by multiple regression analysis (chapter 2-5). It is interesting, considering these data sets, to compare the model's predictive capacity to the predictive power of the multiple regression models, which directly link the subject characteristics with the response. This comparison is presented in Table 3 for body core temperature.

As the empirical regression model was derived from these specific data sets and from the characteristics of actual participating subjects, the explained variance in these regression models may be considered as the maximum achievable explained variance. Comparison of the two model types shows that except for the cool condition, the (independent!) computer model predicts quite well the variance in the data for T_{re} that could be attributed to individual characteristics (last column in Table 3).

Table 3 The correlation coefficients of the predicted T_{re} of the computer simulation model and the real T_{re} data, and the correlation of the predicted T_{re} values by the empirical multiple regression model and the real data. The last column gives the performance of the independent, analytical, computer model as a percentage of the performance of the empirical regression model, the latter based on the data sets used.

condition	number of cases	correlation of model and real T_{re}		r^2 simulation as % of r^2 regression
		r multiple regression model	*r* computer simulation model	
CO/REL	24	0.50	-0.09	-
WH/REL	24	0.71	0.67	89
HD/REL	24	0.31	0.24	60
WH/ABS	82	0.77	0.57	54
HD/ABS	29	0.71	0.65	84

The reason for the deficient prediction in the cool climate may be a too small effect of body fat content on insulation in the model, as in the multiple regression model it was adiposity that had the strongest influence in this condition. The insulative effect of adipose tissue is in the new model strongly dependent on skin blood flow. In the model, for most subjects this increases above 30 $l \cdot m^{-2} \cdot h^{-1}$ for the cool condition, which is about one third of the maximum skin blood flow. In the actual experimental data, the forearm blood flow is for most subjects below 3 $ml \cdot 100ml^{-1} \cdot min^{-1}$, which is about one tenth of the maximum. Thus the insulative effect in the cool condition may well be underestimated due to a too high skin blood flow, which may explain the poor predictive effect for that situation.

6.5 Conclusion

The changes and additions to the original model have improved its general performance, with a reduction in the overall mean error in T_{re}, T_{sk}, and body heat storage by 66 to 83%. Furthermore, the introduction of individual characteristics in the model of human thermoregulation contributed significantly to the model's predictive power for individual's heat stress response. The size of the improvement varied with the climate and the work type, however. The best individual predictions for body heat storage were observed for fixed work loads in a warm, humid and in a hot, dry climate and for work loads relative to the individual maximum in a warm, humid climate (Explained variance 27 - 53%). For relative work loads in a cool and in a hot, dry climate the models predictive capacity for individuals was not significantly improved (<10%).

For all but the cool conditions the predictive power of the analytical simulation model amounts to 54 to 89% of the predictive power of an empirical multiple regression model based on the original data. The latter's predictive power may be seen as maximal achievable predictive power from individual characteristics, thus the analytical model's power is substantial. Nevertheless, still a substantial part of the differences in individual responses remains unexplained (see also suggestions for future research).

References

Åstrand PO, Rodahl K (1970) *Textbook of work physiology*; McGraw-Hill publ New York

Avellini BA, Kamon E (1980) *Physiological responses of physically fit men and women to acclimation of humid heat.* J Appl Physiol 49:254-261

Bean WB, Eichna LW (1943) *Performance in relation to environmental temperature, reactions of normal young men to simulated desert environment.* Fed Proc 2: 144-158

Burton AC, Edholm OG (1955) *Man in a cold environment.* Edward Arnold Publishers LTD, London

Candas V (1980) *Influences de la mouillure cutanée sur l'évolution du débit sudoral et des températures corporelles chez l'homme.* Thèse Université Louis Pasteur, Strasbourg

Candas V, Libert JP, Vogt JJ, (1980) *effect of hidromeiosis on sweat drippage during acclimatization to humid heat.* Eur J Appl Physiol 44:123-133

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

Davies CTM (1981) *Effect of acclimatization to heat on the regulation of sweating during moderate and severe exercise.* J of Appl Physiol 50:741-746

Davies PSW, Jones PRM, Norgan NG (1986) *The distribution of subcutaneous and internal fat in man.* Annals of Human Biology 13: 189-192

DuBois D, DuBois EF 1916) *Clinical calorimetry: a formula to estimate the appropriate surface area if height and weight be known.* Arch Int Med 17:863-871

Eichna LW, Bean WB, Ashe WF, Nelson N (1945) *Performance in relation to environmental temperature, reactions of normal young men to hot, humid (simulated jungle) environment.* Bull. Johns Hopkins Hosp 76:25-58

Fox RH, Goldsmith R, Kidd DJ, Lewis HE (1963) *Acclimatization to heat in man by controlled elevation of body temperature.* J Physiol, London 166:530-547

Gagge AP, Stolwijk JAJ, Nishi Y (1971) *An effective temperature scale, based on a simple model of human physiological regulatory response.* ASHRAE Trans 74:247-262

Gagge AP, Nishi Y (1977) *Heat exchange between human skin surface and thermal environment..* In Handbook of physiology (DHK Lee), 69-92, Bethesda (Chapter 9)

Gagge AP, Fobelets AP, Berglund LG (1986) *A standard predictive index of human response to the thermal environment.* ASHRAE Transactions 92:709-731

Gisolfi CV, Wenger CB (1984) *Temperature regulation during exercise: old concepts, new ideas.* In: RJ Terjung (ed.) Exercise and Sport Sciences Reviews, Lexington, MA Collamore Press

Givoni B, Goldman RF (1972) *Predicting rectal temperature response to work, environment, and clothing.* J Appl Physiol 32:812-822

Givoni B, Goldman RF (1973) *Predicting effects of heat acclimatization on heart rate and rectal temperature.* J Appl Physiol 35:875-879

Gonzalez RR, Pandolf KB, Gagge AP (1974) *Heat acclimation and decline in sweating during humidity transients.* J Appl Physiol 36:419-425

Griefahn B, Schwarzenau P, Bröde P (1992) *Moving between hot dry and warm humid climates.* Proceedings of the 5th int. conf. on environmental ergonomics. Maastricht, nov. 2-6, 1992; eds. Lotens WA and Havenith G

Griefahn B (1994) *The applicability of the WBGT during acclimation.* Proceedings 6th International Conference on Environmental Ergonomics; Montebello, Quebec, Canada, 25 - 30 September 1994; editors: Frim J, Ducharme MB, Tikuisis P

Hardy JD, DuBois EF (1938) *Basal metabolism, radiation, convection and vaporization at temperatures of 22 to 35C.* The Journal of Nutrition 15: 477-497

Hardy JD, DuBois EF (1938) *The technique of measuring radiation and convection.* The Journal of Nutrition 15: 461-475

Havenith G (1985) *Individual parameters in thermoregulatory control; a review.* Report Institute for Perception IZF1985-26

Havenith G, van Middendorp H (1986) *Determination of the individual state of acclimatization.* Report TNO Institute for Perception, 1986-27, Soesterberg, The Netherlands

Havenith G, van Middendorp H (1990) *The relative influence of fitness, acclimatization state, anthropometric measures, and gender on the individuals' reaction to heat stress.* Eur J Appl Physiol 61:419-427

Havenith G, Inoue Y, Luttikholt V, Kenney WL (1995) *Age predicts cardiovascular, but not thermoregulatory, responses to humid heat stress.* Eur J Appl Physiol 70:88-96

Havenith G, Luttikholt GM, Vrijkotte TGM (1995) *The relative influence of body characteristics on humid heat stress response.* Eur J Appl Physiol 70:270-279

Havenith G, Coenen JML, Kistemaker, Kenney L, Kenney WL (1997) *Climate and work load interact with individual characteristics in determining human heat stress responses.* Submitted

Henane R, Bittel J, (1975) *Changes of thermal balance induced by passive sweating in resting man.* J Appl Physiol 38:294-299

Henane R, Flandrois R, Charbonnier JP (1977) *Increase in sweating sensitivity by endurance conditioning in man* J Appl Physiol 43:822-828

Hertzman AB (1957) *Individual differences in regional sweating.* J Appl Physiol 10:242-248

Inoue Y, Havenith G, Kenney WL, Loomis JL, Buskirk ER (1997) *Exercise- and methylcholine-induced sweating responses in older and younger men: effect of heat acclimation and aerobic fitness,* submitted to J Appl Physiol

ISO 7933 (1989) *Hot Environments -Analytical determination and interpretation of thermal stress using calculation of required sweat rate.* Geneva, International Standardization Organization

ISO/TR 11079 *Evaluation of cold environments Determination of required clothing insulation (IREQ)* Geneva, International Standardization Organization

Jackson AS, Pollock ML (1985), *Practical assessment of body composition* the Physician and sports medicine 13:76-90

Kampmann B, Morfeld P, Piekarski C (1992) *Bewertung der ISO 7933: Vergleich der Beanspruchungsprognose der Norm mit Beanspruchungsmessungen bei Felduntersuchungen im Steinkohlenbergbau.* Zeitschrift fur Arbeitswissenschaft, 46 (18 NF) 1992/3

Kobayashi Y, Ando Y, Takeuchi S, Takemura K, Okuda N, Isobe Y, Takaba S, Ohara K (1980) *Effects of heat acclimation of distance runners in a moderately hot environment.* Eur J Appl Physiol 45:189-198

Kuno Y (1956) *Human Perspiration.* Charles C, Thomas, Springfield, llinois

Lotens WA (1993) *Heat transfer from humans wearing clothing* PhD Thesis, Delft University of Technology, February 1993, Delft

Malchaire, J. (1996) *draft document for the BIOMED-2 program "Heat Strain Prediction"*, Université Catholique de Louvain

Mitchel D, Senay, LC, Wyndham CH, van Rensburg AJ, Rogers GG, Strydom B (1976) *Acclimatization in a hot humid environment: energy exchange, body temperature and sweating.* J Appl Physiol 40:768-778

Morrow JR, Jackson AW, Disch, JG, Mood DP (1995) *Measurement and evaluation in human performance.* Human Kinetics, Champaign Ill

Nadel ER, Holmer I, Bergh U, Åstrand PO, and Stolwijk JAJ (1974) *Energy exchange of swimming man.* J Appl Physiol 36:465-471

Nadel ER, Pandolf KB, Roberts MF, Stolwijk JAJ(1974) *Mechanism of thermal acclimation to exercise and heat.* J Appl Physiol 37:515-520

Neale MS, Mishan CE, Withey WR, Parsons KC (1996) *Acclimation of the LUT25-node model (v1.3c) of human thermoregulation.* Report DRA/CHS(HS2)/WP96/020, DRA, Farnborough, UK

Nishi Y, Gagge AP (1977) *Mathematical model of man's heat exchange with his thermal environment.* AICHE symposium series 70:226-232

Pandolf KB, Burse RL, Goldman RF (1977) *Role of physical fitness in heat acclimatization, decay and reinduction.* Ergonomics 20:399-408

Pandolf KB (1979) *Effects of physical training and cardiorespiratory physical fitness on exercise heat tolerance: recent observations.* Med Sci Sports 11:60-65

Pugh LGCE and Edholm OG (1955) *The physiology of channel swimmers.* Lancet 2:761-768

Rennie DW (1988) *Tissue heat transfer in water: lessons from the Korean divers.* Med Sci Sports Exerc 20:S177-S184

Roberts MF, Wenger CB, Stolwijk JAJ, Nadel ER(1977) *Skin blood flow and sweating changes following exercise training and heat acclimation.* J Appl Physiol 43:133-137

Sato K, Sato F (1983) *Individual variation in structure and function of human eccrine sweat gland.* Am J Physiol 245:R203-R208.

Shvartz E, Saar E, Meyerstein N, Benor D, (1973) *A comparison of three methods of acclimatization to dry heat.* J Appl Physiol 34:214-219

Strydom NB, Williams CG (1969) *Effect of physical conditioning on state of heat acclimatization of Bantu labourers.* J Appl Physiol 27:262-265

Stolwijk JAJ, Hardy JD (1966) *Temperature regulation in man - a theoretical study.* Pfluegers Archive 291: 129-162

Stolwijk JAJ, Hardy JD (1966) *Partitional calorimetric studies of responses of man to thermal transients..* J Appl Physiol 21: 967-977

Stolwijk JAJ (1971) *A mathematical model of physiological temperature regulation in man.* Report of NASA contractor, CR 1855

Stolwijk JAJ, Hardy JD (1977) *Control of body temperature.* Handbook of Physiology, sect. 9: reaction to environmental agents, Bethesda, Maryland: American Physiological Society 45-68

Toner MM, Sawka MN, Foley ME and Pandolf KB (1986) *Effects of body mass and morphology on thermal responses in water.* J Appl Physiol 60:521-525

Veicsteinas AG, Ferretti GT and Rennie DW (1982) *Superficial shell insulation in resting and exercising men in cold water.* J Appl Physiol 52:1557-1564

Werner J (1989) *Thermoregulatory models. Recent research, current applications and future development.* Scand. J Work Environ Health 15:34-46

Werner J, Webb P(1993) *A six-cylinder model of human thermoregulation for general use on personal computers.* The annals of physiological anthropology 12: 123-134

Werner J (1993) *Temperature regulation during exercise: an overview.* In; Perspectives in exercise science and sports medicine 6 Exercise, Heat and Thermoregulation; Gisolfi CV Editor

Wissler EH (1964) *A mathematical model of the human thermal system.* Bulletin of mathematical biophysics 26:147-167

Wissler EH (1982) *An evaluation of human thermal models.* Report on a workshop, University of Austin (Tx) dec 13-15

Wood JE, Bass DE (1960) *Responses of the veins and arterioles of the forearm to walking during acclimatization to heat in man.* J Clin Invest 39:825-833

World Health Organisation (1969) *Health factors involved in working under conditions of heat stress.* Report of a WHO scientific group. Wld. Hlth Org. techn. Rep. Ser. No. 412: 5-31

Wyndham CH (1951) *Effect of acclimatization on circulatory responses to high environmental temperatures.* J Appl Physiol 4:383-395

Wyndham CH (1965) *A survey of causal factors in heat stroke and of their prevention in the gold mining industry.* S A J Inst Min Metall, 66: 125-155

Wyndham CH (1967) *Effect of acclimatization on the sweat rate-rectal temperature relationship.* J Appl Physiol 22:27-30

7

Example simulations

Chapter 7
Example simulations

In the previous chapter, the developed computer model was validated against the data sets which were described in chapters 2 to 5. This validation by itself does not provide much information on the versatility of the model in relation to individual characteristics. A good way to provide this information is by presenting examples of model simulations for typical problems encountered in individual heat exposure. This will be done in this chapter. Six examples have been selected related to the following topics:

- the difference in response of an "average" male versus an "average" female
- the response of an obese versus a lean person in the heat
- the response of an obese versus a lean person in a cool climate
- the response of a big versus a small subject
- the effect of acclimation and aerobic power on heat tolerance and water loss in chemical protective clothing
- running a marathon; effect of aerobic power, acclimation and running time

7.1 Man and woman; taking a hike or the bike? (male versus female)

What is the heat strain of an average man or woman who go together on a hiking trip in the heat, on a calm day, both carrying a 10 kg back pack? Can they prepare for that by staying at home and doing the work on an exercise bike with an equal load setting for both in a hot, but well ventilated room?

As described in the previous chapters, the difference in response between males and females on a population bases can be attributed to differences in individual characteristics between the average male and the average female. To see how the model predicts the average responses of the genders, simulations were performed with the following settings derived from tables on population distributions (Morrow et al., 1995; Daanen, personal communication):

Table 1 Parameter settings for male-female simulations with the individualised computer model.

	male	female
age (y)	30	
mass (kg)	75	65
height (cm)	183	170
adiposity (% fat)	20	25
aerobic power (ml $kg^{-1}min^{-1}$)	42	36
acclimatization (days)	0	
metabolic rate ($W\ m^{-2}$) run C	230	257
metabolic rate ($W\ m^{-2}$) run M	260	230

The two work load types represent the following situations:

C Cycling on a cycle ergometer at an external work load of 75 Watt, resulting in a metabolic rate of approximately 450 Watts, at an air velocity of 1.7 $m \cdot s^{-1}$. This load is equal for both genders.

M Marching with a load (clothing + back pack) of 10 kg at a speed of 6 km h^{-1} (air velocity of 1.7 $m \cdot s^{-1}$), no inclination, smooth surface. In this case the metabolic load is dependent on total mass.

To look at the effect of the climate type (i.e. different heat loss pathways), both load types were simulated in a warm humid (WH, 35°C, 80% r.h.) and in a hot dry (HD, 45°C, 20% r.h.) climate. The results for the body core temperatures of these simulations are presented in Fig. 1.

While apparently no steady state is reached in the WH climate, this is reached in the HD conditions. For cycling (1a,c), which represents a lower relative load (%$\dot{V}O_{2\,max}$, load/A_D) to the male, he is at a substantial advantage in both climates. In the marching condition (1b,d), the differences between genders are much smaller. In the HD climate the male has a small advantage, but in the WH climate the female is at an advantage, due to the lower absolute heat liberation in the body for the female and despite the limited heat loss.
Thus, the conclusion is that they will have to adjust the ergometer load to a lower load for the female, if they want to produce a comparable strain to marching.

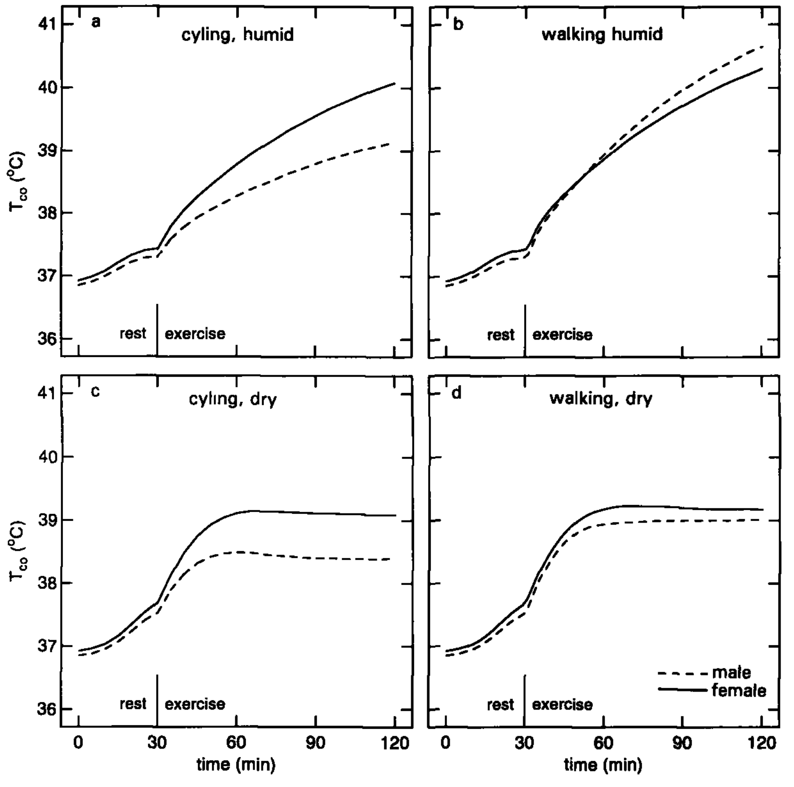

Fig. 1 Results of the simulation runs for a male and a female subject, for the warm humid climate (top) and for the hot dry climate (bottom) with cycling (left) or walking (right) exercise.

7.2 Should we be lean?

A lean and an obese man, dressed in a combat suit, walk (6 km·h^{-1}) together for 90 min after 30 min rest in a WH, a HD and a Cool climate. They have an equal aerobic power and weight and are both unacclimated. They differ in body composition: the lean man has 15% fat, the obese 35%. Is the higher body fat content per se, except for all published associated health risks, also a disadvantage in the heat? What about the cool environment? Does the model show the expected advantage (better insulation) for the obese?

Table 2 Parameter settings for lean-obese simulations.

	lean		obese
age (y)		30	
mass (kg)		80	
height (cm)		183	
adiposity (% fat)	15		35
aerobic power (ml kg^{-1}min^{-1})		40	
acclimatization (days)		0	
metabolic rate (W m^{-2})		250	

Climates HD and WH (Fig. 2a and b) were defined as in example 1. In these climates, only minor differences in the development of body core temperature were observed. Thus nor the difference in body heat capacity between these persons of equal weight, nor the insulating effect of fat had sufficient impact to produce a significant difference in body core temperature response. Overall, the WH climate is more stressful than the HD, though.

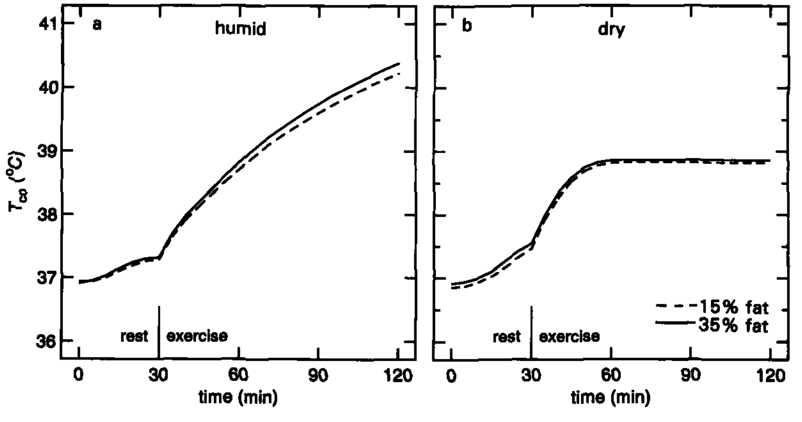

Fig. 2 Effect of obesity on body core temperature response in a warm humid (a) climate and in a hot dry (b) climate.

In the cool climate (10°C, Fig. 3), at rest the lean subject is substantially higher in skin temperature and lower in core temperature (Fig. 3a,b). The obese subject not only has a lower heat loss, but is also better able to preserve the heat generated by shivering in this case. The lean subject has to shiver more (Fig. 3c) to achieve less. The skin blood flow (Fig. 3d) is minimal for both subjects at rest, but when heat has to be lost during exercise, the obese subject has to send more blood to the skin to get rid of the heat in his core. Though he does increase his skin blood flow fast and substantially, it is for a small period insufficient to prevent an overshoot in T_{co} (Fig. 3d and a).

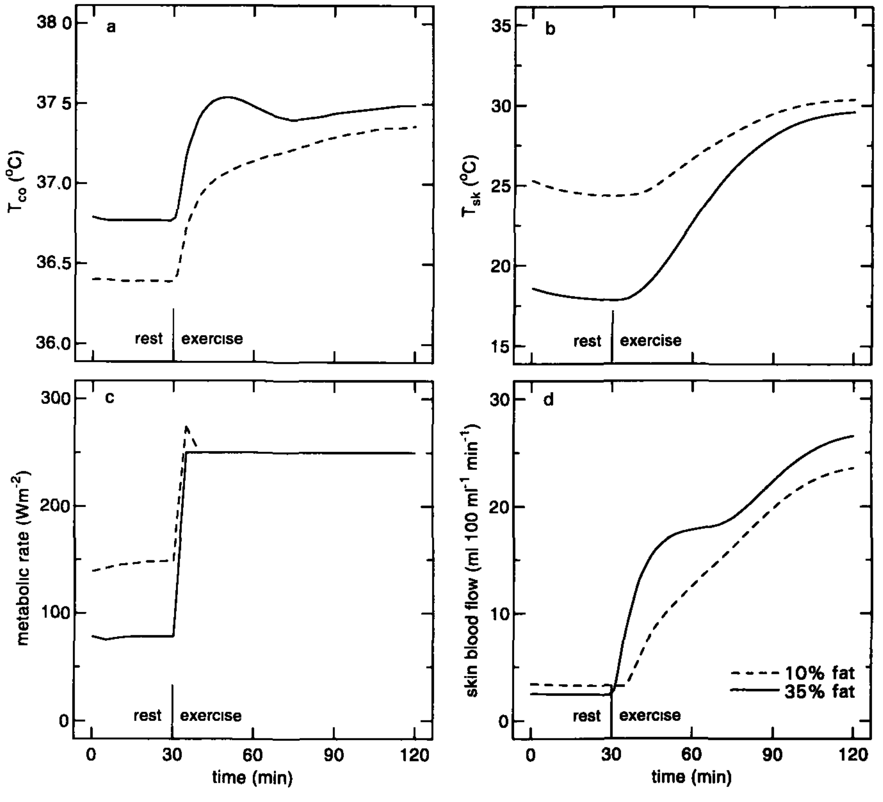

Fig. 3 Effect of obesity on body core- (a) and skin temperature (b), metabolic rate (c) and skin blood flow (d) while resting and exercising in a 10°C environment.

Taking the reaction in the cool climate and the heat together, being in good shape otherwise, having more fat seems an advantage from the thermoregulatory standpoint. On the other hand, obesity usually correlates negatively with being in a good shape.

7.3 The advantage of being big

Body weight below 50 kg is considered a contra-indication for work in the heat (Wyndham and Heyns, 1973). In how far can the low mass and low A_D be blamed for that? As a good correlation exists in the population between $\dot{V}O_{2\,max}$ and mass (within a certain range), the small subject usually has a lower work capacity, and will be more stressed when he has to do the same work as his bigger counterpart (see also Fig. 1a and c). What if except mass and A_D, all other parameters are equal? This is simulated, using the subject of example 2 with 15% fat and masses of 50 and 80 kg. Both work at the same absolute external work load on a bicycle ergometer. The

result for the core temperature prediction is presented in Fig. 4.
For both the WH and HD climates, the bigger subject is at an advantage. He has the same heat production as his small colleague, but he has a bigger surface area for heat loss and his mass provides a bigger heat sink. The model thus supports Wyndham and Heyns finding, although there is no special support for setting the lower limit at 50 kg.

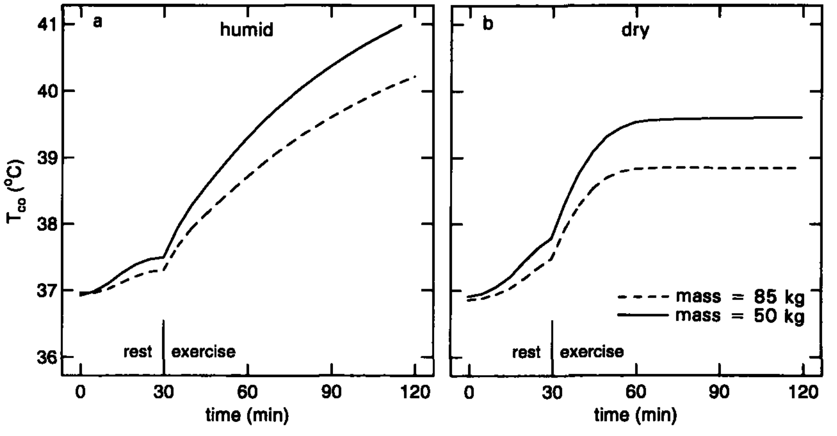

Fig. 4 The effect of different masses on body core temperature response in a warm humid (a) and a hot dry (b) climate.

7.4 Fit for sports! Also fit for work in decontamination suits?

In order to study whether acclimatization and aerobic power are relevant parameters for work in impermeable clothing, two identical subjects (see example 2, lean), except for their aerobic power and their acclimation status, were exposed to a 30°C, 80% humidity environment in a chemical decontamination suit, including respirator and gloves. One subject was set at the moderate fitness, a $\dot{V}O_{2\,max}$ of 30 ml kg^{-1} min^{-1} with 0 acclimation days, the other at the high level of 60 ml kg^{-1} min^{-1} and 15 acclimation days. The responses for core and skin temperature and for accumulated water loss are presented in Fig. 5.
As the microclimate in the suits becomes saturated fast with water vapour, the effectivity of sweating is strongly reduced. Evaporative heat loss is limited by the microclimate and not by sweat production. In the saturated microclimate heat loss from the skin is dependent on skin temperature only and not on the subject's acclimation state or his aerobic power. This is reflected in the skin temperature response: after a small difference in the transient state, skin temperatures of both subjects become equal and rise with the same rate (Fig. 5b). The same is then

expected to happen with core temperature. The rate of rise indeed is identical for both subjects, but due to the lower skin blood flow and the higher relative work load, T_{co} is higher for the moderate fit person (Fig. 5a). This lower blood flow necessitates a higher gradient between core and skin to get the same heat transport. Thus the moderate fit person will cross the risk level of T_{co} earlier. The dripping sweat causes in increasing difference in total body water loss between the subjects (Fig. 5c) even though the difference in T_{co} stayed equal. Looking at a maximal dehydration level, the moderate fit person would be able to perform longer than the fittest, who sweats most. For this type of work the answer to the question which limit will be reached first, the T_{co} limit or the dehydration limit is determined by the work rate and the environmental temperature. Are these such that T_{co} rises slowly (low work, low climatic load), the dehydration will become dominant and the fittest person will drop out first. For a fast rising T_{co}, the moderate fit worker will drop out first. Using the model, varying the climate conditions allows the user to analyse the risk for specific situations.

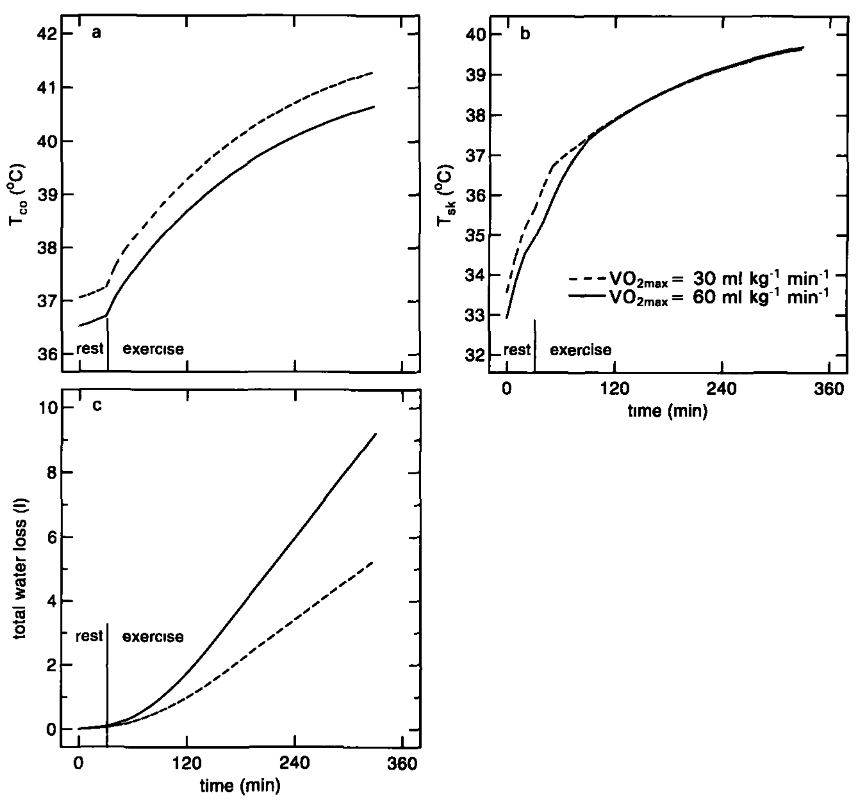

Fig. 5 The effect of aerobic fitness and acclimation on responses of core- (a) and skin (b) temperature and of total body water loss (c).

7.6 Marathon time and heat exhaustion risk

Running a marathon in a warm climate is not without risk. In order to look at the risk of overheating, simulation runs were obtained for a top athlete (running scheme time 2:10) with and without heat acclimation, and for a partially acclimated runner with a top time of 2:35. Energy expenditure was derived from the relation between running speed and efficiency for top long distance runners and slower runners (data for middle distance runners used) as given by Fox and Costill (1972):

Table 3 Parameter settings for runners simulations

	top runner	slower runner
age (y)	30	
mass (kg)	65	
height (cm)	180	
adiposity (% fat)	15	
aerobic power (ml O_2 $kg^{-1}min^{-1}$)	85 (model limit 60)	60
acclimatization (days)	0 15	4
running speed (m min^{-1})	325	270
energy cost (ml O_2 m^{-1} kg^{-1})	0.17	0.18
Metabolic rate (W m^{-2})	697	617

The climates used were 30°C, 80% r.h. for the humid condition and 38°C, 20% r.h. for the dry condition. The results for the development of T_{co} are presented in Fig. 6a and b. For the dry climate (Fig. 6b) both the acclimated top runner as well as the "slow" runner are able to run with a steady state core temperature. As this is around 40°C, it is questionable whether the "slow" runner can actually tolerate this. The top runner probably can, as for most top athletes tolerances to temperatures above 40°C have been observed. For the top runner, the steady state reached is a critical one. If he were unacclimated, he would not be able to achieve sufficient evaporative cooling due to insufficient sweat production, and his temperature would continue to rise, as seen in Fig. 6b.

For the humid climate, running a 2:10 marathon is more critical for body temperature (Fig. 6a). Here the slow runner again stabilises around 40°C, but the top runner does not reach a steady state. If acclimatized he may be able to finish his run just above 41 °C, but unacclimatized a finish in that time is quite unlikely.

To illustrate the effect of running time on T_{co} development, this relation is presented in Fig. 6c for a partially (4 days) acclimatized top-runner. This graph shows that for the chosen subject a steady state in core temperature is possible up to a running time of 2:15. In order to run at that steady state, he has to be able to tolerate a core temperature of up to 40.3°C. Running faster in the simulated climate, results in a continuous increase in T_{co}, and heat exhaustion, before the finish line, will be inevitable. These findings are in line with the risk assessment of the climate (38 °C, 20% r.h.) based on the Heat Stress Index, which indicates high heat stress, and on the ACSM guidelines based on WBGT which suggest a moderate heat stress (Vogel et al., 1993).

The effect of dehydration was not considered in these runs. This is expected to aggravate the risk.

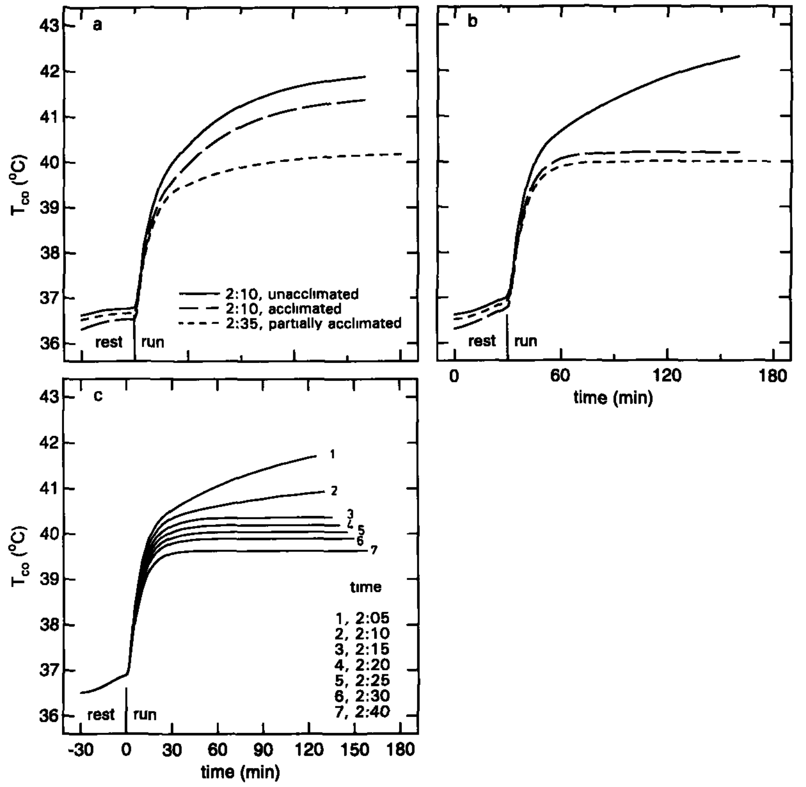

Fig. 6 Body core temperature response while running a marathon in a warm humid (a, c) or a hot dry (b) climate at different speeds.

References

Fox Costill D (1972) *Estimated cardiorespiratory responses during marathon running*. Arch. Env. Health 34, 322-326.

Morrow JR, Jackson AW, Disch, JG, Mood DP (1995) *Measurement and evaluation in human performance*. Human Kinetics, Champaign Ill

Vogel JA, Rock PB, Jones BH, Havenith G (1993) *Environmental considerations in exercise testing and training;* Resource manual for guidelines for exercise testing and prescription, 2nd edition,

American College of Sports Medicine, Lea & Febiger, Philadelphia.
Wyndham CH, Heyns AJ (1973). *Quantitative prediction of physiological and physiological effects of thermal environment in man; the probability of heat stroke developing at different levels of heat stress.* Colloques Internationaux du Centre National de la Recherche Scientifique, No. 225, Strasbourg, 9-13 Juillet 1973.

8

Summary and suggestions for future research

Summary and suggestions for future research

This thesis deals with individual heat strain. Individuals show large variations in their reactions to exercise in the heat. Knowledge of the cause for this variation can be used in various ways, e.g.: - for selection: who will be most fit to do specific stressful jobs in the heat; - for screening and risk assessment; - for work optimization: tuning the work population to the task and vice versa. Once this knowledge is introduced into heat stress standards and simulation models, it is quantified and accessible to a wide range of users. Such models will improve risk assessment and also allow training of people who work on heat stress assessment.

Chapter 1 explains the need for improved heat stress prediction, and more specifically the need to incorporate individual characteristics in the prediction models. The literature on the topic of the relation between individual characteristics and heat stress response is summarized, pointing out the main individual characteristics which are expected to be of importance: aerobic power ($\dot{V}O_{2\,max}$), morphology (height, mass, body surface area [A_D] surface-to-mass ratio [A_D/mass]) and body fat content (%fat), acclimatization state, hydration state, gender and age, differences in circadian rhythm, presence of hypertension and the use of drugs. The literature suggests that $\dot{V}O_{2\,max}$, morphology and acclimation state are the most important parameters, but does not provide an estimate of the relative importance of the separate factors. For the study of this topic an alternative method is presented. This comprises the use of heterogeneous subject groups, instead of groups differing in only one parameter as commonly found in literature, and the analysis using multiple regression techniques, in order to determine the importance of different characteristics in relation to each other. The parameters selected for this study are: aerobic power, anthropometrics and morphology, gender and age. The others were held constant.

In chapter 2, the effect of age versus that of other individual characteristics was investigated. A group of 56 subjects was exposed to a warm humid climate (35°C, 80%, <0.2 m·s^{-1} wind) , all working at the same absolute load on the cycle ergometer (60 W). While the subject groups discussed in the next chapters were selected within a narrow age range, this group ranged in age from 20 to 73 years, with approximately 10 subjects per decade. Subjects were selected such that no correlation of age with $\dot{V}O_{2\,max}$ was present. Age is found not to have a significant effect on rectal temperature, body heat storage or sweat loss. All of these were closely related to $\dot{V}O_{2\,max}$. On the other hand heart rate, mean arterial pressure (MAP) and forearm vascular conductance (FVC) were related to both age and $\dot{V}O_{2\,max}$. It is concluded that chronological age has a negligible effect on body temperature and sweating, but that age has an independent effect on cardiovascular effector response.

In chapter 3, the warm humid climate experiment of chapter 2 was repeated, concentrating on differences within the young group. To this purpose the youngest subjects of the experiment from chapter 2 were taken and the group was supplemented with additional subjects to a total of 27. In this case, body temperatures and heat storage are determined predominantly by $\dot{V}O_{2\,max}$. A_D /mass also contributed to the variance in body core temperature, but with about half the effect of $\dot{V}O_{2\,max}$. Total body sweat loss was highly dependent on body size, and a factor of 4 less on regular activity level. The heart rate, similar to T_{re}, was determined by $\dot{V}O_{2\,max}$. A_D or A_D /mass had less than half of that effect. Other circulatory parameters (FBF, MAP, FVC) showed little relationship with individual characteristics. In general, the higher the $\dot{V}O_{2\,max}$ and/or the bigger the subject, the lower the heat strain observed. The widely accepted concept, that body core temperature is determined by exercise intensity expressed as $\%\dot{V}O_{2\,max}$ and sweat loss by absolute heat load, is only partially supported by these results. For both variables, other individual characteristics are also shown to contribute.

In chapter 4, data from 24 subjects exposed to a cool, warm-humid and a hot-dry climate (21 °C, 50% rh; 35 °C, 80%; 45 °C, 20%; all <0.2 $m \cdot s^{-1}$ wind) working at a load relative to the individual maximum (cycle ergometer, 45% $\dot{V}O_{2\,max}$) are discussed. The data were first lumped over climate types to see which characteristics determined the overall response to work in different climates. Body mass and daily activity level were the most relevant factors.
As, based on the findings of chapter 1, an interaction between climate type and individual characteristics in their effect on the physiological response (core temperature, heat storage, heart rate) was expected, the data were then statistically analysed for the presence of such an interaction. For this purpose, the differences in responses between the three climates were analysed for the presence of effects of individual characteristics. As significant effects were observed ($\dot{V}O_{2\,max}$, ACTIV, %fat; a trend for gender), it was concluded that the interaction was present. This interaction was further investigated in chapter 5.
In the multiple regression analyses of the differences in response between the climates, $\dot{V}O_{2\,max}$, %fat, ACTIV, and body mass were found to be relevant parameters. Gender lost its influence once data were corrected for $\dot{V}O_{2\,max}$ or %fat.

Chapter 5 integrates the findings of the experimental work. The data from the experiments of chapters 2 and 4 were analysed together with those from a new experiment in which 30 subjects were exposed to a hot-dry climate, exercising at a

fixed work load (60W) to complete the hot climates × work loads design. The emphasis of the analysis was on core temperature response and its relation with individual characteristics. Individual characteristics interact with the climate type (cool, warm-humid, hot-dry) and the work type (relative or fixed work loads). Results suggest that a high mass is beneficial (i.e. low strain) for the individual's heat strain as defined in T_{re} or heat storage increase. A high $\dot{V}O_{2\,max}$ is beneficial for all tested conditions, except for the relative work load in the warm-humid environment. There, as evaporative heat loss is limited, the higher heat production of fitter subjects in the relative work load trials determines T_{re} and not the greater heat loss efficiency associated with high $\dot{V}O_{2\,max}$. %Fat significantly affected T_{re} only in the cool condition. There, with low skin blood flows (measured as increases in forearm blood flow), the insulative effect of fat is pronounced. In the warm environments, high skin blood flows offset the resistance offered by peripheral adipose tissues. Contrary to other publications, T_{re} was positively correlated with A_D/mass ratio for all conditions tested. For both exercise types used, being big (a high heat loss area and heat capacity) is apparently more effective against heat strain than having a favourable area to mass ratio (high in small subjects). Gender, in general lost its influence once data were corrected for the effects of $\dot{V}O_{2\,max}$, mass, or of %fat.
The total amount of variance in T_{re} responses which could be attributed to individual characteristics was dependent on the climate and work type. Though the explained variance in T_{re} is substantial for absolute work loads (52-58%) it differed strongly for relative loads: 72% for the WH climate with its limited evaporative capacity, and only 10-26% for the HD and CO climates. The results show that individual characteristics play a significant role in the determination of body core temperature response in all conditions tested, but their contribution is low for relative work loads when evaporative heat loss is not restricted. This study demonstrates that effects of individual characteristics on human heat stress responses cannot be interpreted without taking into consideration both the heat transfer properties of the environment and the metabolic heat production resulting from the exercise type and intensity chosen. Their impact varies substantially between conditions.

In chapter 6, a computer model of human thermoregulation was adapted to incorporate individual characteristics. Data from literature were used to estimate relevant parameters for the model. Effects of body surface area, mass, fat content, training and acclimation were incorporated. Next, the data sets from chapters 2 to 5 were used to validate the model against. The changes and additions to the original model improved its general performance, with a reduction in the overall mean error in T_{re}, T_{sk}, and body heat storage by 66 to 83%. Also on an individual basis an improved prediction was observed. The size of the improvement varies with the climate and the work type, however. The best predictions for body heat storage are observed for fixed work loads in a warm humid and in a hot dry climate and for work loads relative

to the individual maximum in a warm humid climate (explained variance 27 - 53%). *For relative work loads in a cool and in a hot dry climate the models predictive* capacity for individuals is not significantly improved (<10%).
When this predictive power was compared to that of a multiple regression model derived from these data sets (the "maximal achievable" predictive power), using individual characteristics as independent parameters and body temperature as dependent variable, the results showed that the analytical computer simulation model (developed independently of the datasets used) has between 54 and 89% of the predictive power of the empirical regression model (chapter 5), except for the cool climate where this is zero. In that climate, the regression model has little predictive power too, however, so the variance in those data has to be attributed to other parameters than studied here (see suggestions for future research).

In chapter 7, six typical problems related to individual characteristics, some of practical relevance, some of theoretical interest, were simulated by the individualized model. Results are clear illustrations of the model's capabilities and of the mechanisms behind individual variance in heat stress response.

From the studies presented in this thesis, it can be concluded that the knowledge on the relation between a number of individual characteristics and heat stress response, and their relative importance has been improved. The addition of individual characteristics to the computer model provides a good tool to study effects of these characteristics. Furthermore, the introduction of individual characteristics in the model of human thermoregulation contributed significantly to the model's predictive power. However, it also must be concluded that a substantial part of individual variation is still not understood. This must have another source than those included in this study.

Future research

The remaining unexplained differences are of course worth future attention.

- It is quite likely that there is a large genetic component in these differences, which is not related to aerobic power, physical activity level, body composition, mass, A_D, etc.
- Most studies, including this thesis, have focussed on overall body responses for sweating, as opposed to regional responses. Regional differences in sweat production may be able to explain different heat strain in subjects with e.g. similar overall body sweat rates. One of the positive effects of acclimation e.g. is a better distribution of sweat over the skin surface, leading to more efficient sweating (evaporation/production ratio). This regional distribution may well be

an important factor in the determination of individual differences in heat stress response too (Kuno 1956; Inoue, personal communication). A study of how this regional distribution of sweating may be linked to other personal characteristics may therefore be quite relevant.

- A single persons heat stress response is shown to be very variable on a day to day basis (Livingstone, 1992). It is for the presented data impossible to say whether and how much of the observed unexplained variation in the responses is actually due to this day to day variance. An analysis of the average response over a couple of days may show a higher correlation with individual characteristics than a single response. What causes these day to day differences?
- One parameter often neglected in modelling is the work efficiency of subjects. In sports science significant differences in energetic efficiency during running have been described for different athletes (Fox and Costill, 1972). Typical marathon runners have, at equal speed, an up to 10% higher efficiency (here defined as distance covered per unit of energy) than middle distance runners. This leads to substantial differences in heat liberation in the body at equal external work rates. In the validation of the current model this effect was taken care of by using actually measured metabolic rates where possible. For general use of the model, an investigation of the relation between work efficiency and individual characteristics may be fruitful.

In the model chosen as starting point, not all control parameters appeared to be realistic in magnitude. Sweat rate e.g., has a gain factor for the average person which amounts to 170 $g{\cdot}m^{-2}{\cdot}h^{-1}{\cdot}°C^{-1}$. In order to reach maximal sweat rates estimated between 1 and 2 $l{\cdot}m^{-2}{\cdot}h^{-1}$, the increase in core temperature (at constant T_{sk}) would have to be over 6 °C. A higher gain seems therefore more realistic. This was incorporated in the model, but resulted in an overall underestimation of heat strain. Thus, this underestimated gain of sweating is apparently compensated for by other factors in the model.

As the main purpose of this study was to determine the possibilities of individualization, the average gain was less important than the differentiation in gain between individuals. For that reason this topic was not further pursued at this time. Leads to follow on this subject are e.g. sweat evaporative efficiency and sweat delay.

In order to provide a better understanding of the processes which take place in heat exposure, control equations with realistic control parameters would obviously be preferable and therefore this point should be addressed in future.

References

Fox RH and Costill DL, (1972) *Estimated cardiorespiratory responses during marathon running* Arch. Env. Health 24, 322-326

Inoue Y (1996) personal communication

Kuno Y (1956) *Human perspiration*, Charles Thomas publisher, Springfield, IL.

Livingstone SD, Nolan RW, Keefe AA (1992) *Variability of body temperature response to standardized stress conditions*, Proc. 5th int. conf. on Environmental Ergonomics, Lotens WA and Havenith G., eds.

9

Samenvatting en aanbevelingen voor verder onderzoek

Samenvatting en suggesties voor verder onderzoek

Dit proefschrift gaat over de verschillen tussen individuele personen in reactie op hittebelasting. Deze verschillen zijn substantieel. Dit levert problemen als een uitspraak gedaan moet worden over hoe belastend bepaalde werkzaamheden in de warmte zijn. Waar de ene persoon nog nauwelijks belast is, kan een ander al de grens voor een hittecollaps of hitte-uitputting bereikt hebben. Dat heeft er in het verleden toe geleid dat alle normen en modellen voor de bepaling of voorspelling van de mate van hittebelasting van groepen mensen bij het opgeven van tolerantiecriteria een zeer grote veiligheidsmarge hebben aangehouden. Daardoor was in de praktijk de veiligheid van 99% van de werknemers verzekerd, maar kon soms nauwelijks enige produktiviteit bereikt worden. Kennis van de verschillen en van de oorzaken voor de verschillen tussen individuen kan op een aantal manieren worden toegepast, zoals bijvoorbeeld voor selectie: wie van de groep werknemers of militairen is het meest geschikt voor zwaar belastend werk in de hitte, voor medische screening van mensen, voor risicoanalyse, en voor optimalisatie van de taak-kleding-mens relatie.
Als deze kennis ook kwantitatieve relaties tussen individuele kenmerken en hitte respons omvat, kan deze in de eerder genoemde normen en computerprogramma's voor de berekening van hittebelasting worden ingebracht. Zulke normen en modellen zullen dan tot een betere risicoschatting leiden dan op dit moment ermee mogelijk is, en ze zijn ook geschikt voor het verkrijgen van inzicht in de materie in het kader van trainingen en opleidingen.

Uit de literatuur (hoofdstuk 1) blijkt dat de volgende factoren een rol spelen bij de individuele reactie op hitte: het aërobe prestatievermogen (maximale arbeid die iemand op basis van volledige verbranding van voedingsstoffen met zuurstof kan leveren [$\dot{V}O_{2\,max}$]), de morfologie (lichaamsoppervlak [A_D], oppervlakte-massa verhouding [A_D /mass]) en het vetgehalte van het lichaam (%fat), de mate van acclimatisatie (aanpassing aan warmtebelasting), de vochtbalans van het lichaam, geslacht, leeftijd, verschillen in circadiane ritmes, hypertensie en geneesmiddelengebruik. Van deze parameters wordt de grootste relevantie verwacht van $\dot{V}O_{2\,max}$, morfologie en acclimatisatiegraad. De literatuur levert geen schatting van het relatieve belang van de verschillende individuele karakteristieken.
Om de effecten van deze parameters in kaart te brengen is in hoofdstuk 2 tot en met 5 experimenteel werk beschreven waarbij groepen proefpersonen met verschillende arbeidsbelastingen aan verschillende klimaten zijn blootgesteld, waarna de relatie tussen hun fysiologische reactie en hun individuele kenmerken is geanalyseerd. De voor dit onderzoek geselecteerde kenmerken waren: het aërobe prestatievermogen,

massa, oppervlakte, oppervlakte-inhoud verhouding, vetgehalte, geslacht en leeftijd. De overige werden constant gehouden. Voor dit onderzoek wordt in dit proefschrift een alternatieve onderzoeksmethode voorgesteld. Deze bestaat uit het gebruik van heterogene groepen proefpersonen en analyse van meerdere parameters tegelijk, in plaats van groepen die op slechts één aspect verschillen zoals in de literatuur gebruikelijk. Daarvoor wordt in deze methode gebruik gemaakt van multipele regressie als analysemethode teneinde het relatieve belang van verschillende parameters in kaart te brengen.

De onderzoeken van hoofdstuk 2 tot en met 5 betreffen blootstellingen aan warm-vochtige klimaten (35°C, 80% r.v.) en heet-droge klimaten (45°C, 20%r.v.), waarbij óf gewerkt wordt met een belasting die aangepast is aan het maximale prestatievermogen van de persoon, óf gewerkt wordt met dezelfde belasting voor alle personen. Hoofdstuk 2 bespreekt een experiment in het warm-vochtige klimaat bij een vaste arbeidsbelasting waarbij met name naar het leeftijdsaspect gekeken is, hoofdstuk 3 gebruikt dezelfde conditie als hoofdstuk 3, maar concentreert zich op een (uitgebreide) jonge populatie. Hoofdstuk 4 bespreekt alle relatieve belastingstesten, waarbij ook nog in een koel (21°C, 50%r.v.) klimaat gemeten is. In hoofdstuk 5 worden nieuwe data over een vaste arbeidsbelasting in een heet droog klimaat toegevoegd aan de overige data en wordt een integrale analyse van alle data (uitgezonderd de leeftijddata) besproken.

Voor de leeftijddata (hoofdstuk 2) bleek dat over een groot bereik van leeftijden (20 tot 73 jaar), waarbij proefpersonen zo werden geselecteerd dat tussen leeftijd en het aërobe prestatievermogen ($\dot{V}O_{2\,max}$) geen correlatie bestond, leeftijd geen aantoonbaar effect op de kerntemperatuur van de groep had, noch op de warmteopslag of de zweetproduktie. Deze waren alle sterk gerelateerd aan de $\dot{V}O_{2\,max}$. De gemiddelde bloeddruk (MAP) en de vasculaire geleiding van de onderarm daarentegen, waren beide gerelateerd aan leeftijd en $\dot{V}O_{2\,max}$. Geconcludeerd wordt dat leeftijd een verwaarloosbaar effect heeft op lichaamstemperatuur en op zweten, maar ook dat de chronologische leeftijd een onafhankelijk effect heeft op de cardiovasculaire respons.

Voor de overige data (hoofdstuk 3,4 en 5) bleek dat de individuele kenmerken een sterke interactie met het klimaattype (koel, warm-vochtig, heet-droog) en met het arbeidstype (relatieve of vaste belasting) vertonen. De resultaten geven aan dat een grote massa gunstig is (lage fysiologische belasting) in termen van de rectaaltemperatuur of warmteopslag toename. Een hoge $\dot{V}O_{2\,max}$ is gunstig in alle condities behalve voor de relatieve arbeidsbelasting in het warm-vochtige klimaat. In dat klimaat is de warmteafgifte zo beperkt dat de hogere interne warmteproduktie bij fittere mensen (bij relatieve belasting) bepalend is voor de rectale temperatuur en niet de grotere effectiviteit van hun warmteafgiftemechanismen. Het vetgehalte blijkt alleen in een koel klimaat een effect op de rectaaltemperatuur te hebben. In die conditie is het isolerende effect van vet substantieel. In warmere omstandigheden zorgt de verhoogde doorbloeding van vet en huidlagen ervoor dat de warmteweerstand van de vetlaag ineffectief wordt.

In tegenstelling tot andere publicaties bleek de rectaaltemperatuur positief gecorreleerd te zijn met de oppervlakte-inhoud verhouding van het lichaam, en wel in alle gemeten omstandigheden. Blijkbaar is een groot lichaam voor de gegeven condities (een groot oppervlak voor warmteafgifte en een grote massa voor warmteopslag) gunstiger voor het laag houden van de kemtemperatuur dan een hoge oppervlakte inhoud verhouding (groot bij kleine mensen).

Het geslacht van de persoon bleek op diverse fysiologische reacties van invloed. Als echter eerst gecorrigeerd werd voor verschillen tussen de proefpersonen in maximaal prestatievermogen, massa of vetgehalte, dan verdwenen deze "geslachts" gerelateerde verschillen.

De grootte van de variantie in de rectaaltemperatuur die kan worden toegeschreven aan individuele kenmerken blijkt afhankelijk van het type klimaat en het type arbeid. Hoewel de hoeveelheid verklaarde variantie groot is voor de absolute arbeidsbelasting (52-58%) verschilt deze sterk voor de relatieve belastingscondities: 72% voor het warm vochtige klimaat met zijn gelimiteerde warmteafgiftecapaciteit, en slechts 10 tot 26% voor het heet-droge en het koele klimaat. De resultaten tonen dat individuele kenmerken een significante rol spelen bij het bepalen van de lichaamstemperatuur in alle geteste condities, maar dat hun bijdrage klein is bij relatieve inspanningsniveaus als de warmteafgifte niet is beperkt. Deze studie laat zien dat effecten van individuele kenmerken niet kunnen worden geïnterpreteerd zonder rekening te houden met de warmtewisselingseigenschappen van het klimaat, en met de warmte die vrijkomt in het lichaam ten gevolge van een bepaald type en intensiteit van arbeidsbelasting. Hun effect varieert sterk tussen condities.

In hoofdstuk 6 is beschreven hoe op basis van literatuurgegevens een computermodel van de thermoregulatie is bewerkt en individuele kenmerken daarin zijn geïmplementeerd. Effecten van lichaamsoppervlakte, massa, vetgehalte, training of verschillen in maximaal prestatievermogen en acclimatisatie werden gemodelleerd. Vervolgens werden de data van de voorgaande hoofdstukken gebruikt om het aangepaste model te valideren. De kwaliteit van de berekeningen bleek verbeterd, zowel wat betreft de gemiddelde afwijking tussen berekende en gemeten waarde, alsook wat betreft de verbetering van de individuele voorspelling. De kwaliteit van de voorspellende berekeningen bleek echter ook sterk te verschillen tussen de gebruikte meetcondities. De beste schattingen van de hittebelastingsrespons werden bereikt voor vaste arbeidsbelastingen in een warm-vochtige en heet-droge omgeving, en voor werk relatief aan het individuele maximum in een warm-vochtig klimaat. (verklaarde variantie 27-53%). Voor relatieve belastingen in een koel en in een heet-droog klimaat leverde het model geen duidelijk verbeterde schattingen. Deze voorspellende waarde werd vergeleken met die van een multipel regressiemodel (hoofdstuk 5), dat op de data zelf was gebaseerd (de maximaal haalbare voorspellingskracht voor deze data). Het onafhankelijk van de datasets opgestelde computermodel bleek tussen de 54 en de 89% van de voorspellende waarde van het empirische regressiemodel te halen, behalve voor het koele klimaat waar dit nihil was. In dat laatste klimaat had het regressiemodel echter ook maar een minimale voorspellingskracht.

In hoofdstuk 7 worden met het model zes voorbeeldsituaties doorgerekend met het geïndividualiseerde model, deels geselecteerd vanuit praktische relevantie, deels vanuit theoretische interesse. De resultaten zijn duidelijke illustraties van de mogelijkheden van het model en van de onderliggende mechanismen van de individuele variantie in hittebelastingsrespons.

Op basis van de in dit proefschrift beschreven studies kan worden gesteld dat de kennis over individuele variantie in hittebelastingsrespons is toegenomen. De toevoeging van individuele kenmerken en daar achterliggende mechanismen aan een computermodel leverde een bruikbaar gereedschap op om deze effecten te bestuderen en maakt een verbeterde voorspelling van hittebelasting mogelijk. Helaas blijkt echter nog een substantieel deel van verschillen tussen personen in hitterespons onverklaard. De oorzaken daarvan moeten worden gezocht in andere mechanismen dan hier bestudeerd.

Toekomstig onderzoek

De resterende onverklaarde variantie in de reactie op hitte verdient uiteraard de aandacht.

- Het is zeer waarschijnlijk dat er een belangrijke genetische component in deze verschillen aanwezig is die niet gerelateerd is aan parameters als aëroob prestatievermogen, activiteitenniveau, lichaamssamenstelling, massa, lichaamsoppervlak, etc.
- Veel studies, inclusief dit proefschrift, hebben zich vooral gericht op de respons van het lichaam als geheel. Het is echter mogelijk dat juist regionale verschillen in zweetproduktie over het lichaam, verschillen tussen individuen die dezelfde totale zweetproduktie vertonen kunnen verklaren. Een van de positieve kanten van acclimatisatie is bijvoorbeeld een betere distributie van de zweetproduktie over het lichaam, waardoor de zweet efficiëntie (verdampt/geproduceerd) toeneemt. Deze regionale verdeling zou wel eens een relevantere factor voor de verklaring van individuele verschillen in hitterespons kunnen zijn dan in het

verleden gedacht (Kuno, 1956; Inoue, persoonlijke communicatie). Studie van de relatie tussen de regionale zweetdistributie en persoonlijke kenmerken kan derhalve van nut zijn.

- De hittebelastingsrespons van individuen blijkt nogal te varieren per meetdag (Livingstone, 1992). Voor de in dit proefschrift gepresenteerde data is het niet mogelijk te schatten of, en in welke mate, de geobserveerde onverklaarde variantie juist aan deze dag tot dag variatie in respons toe te schrijven is. Een analyse gebruik makende van de gemiddelde respons van proefpersonen op eenzelfde test over meerdere metingen, laat mogelijk een hogere correlatie zien met individuele kenmerken dan een enkele respons. Een belangrijke vraag is wat de oorzaak van deze test-hertest variatie is.
- Een vaak verwaarloosde parameter bij het modelleren van inspanning is de metabole efficiëntie waarmee het werk wordt verricht: hoeveel energie heeft iemand nodig om een bepaalde taak te verrichten? In de sportwetenschap zijn significante verschillen tussen atleten in energetische efficiëntie bij het lopen van lange afstanden beschreven (Fox en Costill, 1972). Specialistische marathonlopers hebben een tot 10% hogere efficiency (uitgedrukt in gelopen afstand per eenheid van energie) dan middellange afstandslopers. Dit leidt, bij gelijke loopsnelheid tot forse verschillen in metabolisme, en zodoende tot forse verschillen in de hoeveelheid in het lichaam vrijkomende warmte. In de validatie van het in dit proefschrift gepresenteerde model is met dit effect rekening gehouden door de werkelijk gemeten metabole energieproduktie in te vullen. Voor algemeen gebruik van het model, zou een onderzoek naar de relatie tussen deze efficiency en individuele kenmerken echter zeker zinvol zijn.

In het als startpunt gekozen model bleken niet alle regelkarakteristieken en parameters realistisch in grootte. De zweetproduktie bijvoorbeeld heeft een gain-factor (de stijlheid van de relatie met de lichaamstemperatuur) voor de gemiddelde persoon van 170 $g \cdot m^{-2} \cdot h^{-1} \cdot {}^{\circ}C^{-1}$. Om tot maximale zweetprodukties, die geschat worden op 1 tot 2 $l \cdot m^{-2} \cdot h^{-1}$, te komen zou de kerntemperatuur van het lichaam (bij constante huidtemperatuur) met zo'n 6°C moeten toenemen. Een hogere gain waarde lijkt derhalve realistisch. Bij invoering daarvan in het model bleek echter dat de hittebelasting daardoor fors werd onderschat. Dit suggereert dat de te lage gain in het originele model wordt gecompenseerd door andere factoren in het model.
Daar het hoofddoel van deze studie het onderzoeken van de mogelijkheden van individualisatie was, was de gemiddelde gain minder relevant dan de variatie in gain tussen individuen. Om die reden is het onderzoek naar aanpassing van de gemiddelde gain niet voortgezet. Sporen die wat dit onderwerp betreft gevolgd kunnen worden zijn de efficiëntie van de zweetproduktie (verdampt/geproduceerd) en de vertraging die in de zweetproduktie kan optreden ten opzicht van een stijgende kerntemperatuur. Teneinde een beter inzicht in de processen te krijgen die de mate van hittebe-

lasting van het lichaam bepalen, zijn modellen met realistische regelparameters uiteraard te prefereren, hetgeen verder onderzoek op dit punt wenselijk maakt.

Referenties

Fox RH and Costill DL, (1972) *Estimated cardiorespiratory responses during marathon running* Arch. Env. Health 24, 322-326

Inoue Y (1996) personal communication

Kuno Y (1956) *Human perspiration*, Charles Thomas publisher, Springfield, IL.

Livingstone SD, Nolan RW, Keefe AA (1992) *Variability of body temperature response to standardized stress conditions*, Proc. 5th int. conf. on Environmental Ergonomics, Lotens WA and Havenith G., eds.

Appendix 1
Program code

part of the program code,
specifically related to the individualized model;

```
      SUBROUTINE INDIN
C     This subroutine deals with the input of the characteristics,
C     and the calculation of the effects on model parameters.
C
$INCLUDE:'THINDIV0.FOR'
C     changes for initialization of individual differences
      WRITE(*,'(/," Give the persons body weight in kg ",
 >          "(now ",F6.1,"kg):",\)')W
      CALL GET(W)
      WRITE(*,'(/," Give the persons height in m ",
 >          "(now ",F6.2,"m):",\)')HEIGHT
      CALL GET(HEIGHT)
      WRITE(*,'(/," Give the persons body fat percentage ",
 >          "(now ",F6.1,"%):",\)')PFAT
      CALL GET(PFAT)
      WRITE(*,'(/," Give the persons age ",
 >          "(now ",F6.1,"):",\)')AGE
      CALL GET(AGE)
      WRITE(*,'(/," Give the persons gender (M/f)",\)')
      READ(*,'(A1)')DUM
      IF (DUM.EQ.'f'.OR.DUM.EQ.'F') THEN
                SEX='F'
      ELSE
                SEX='M'
      ENDIF
      WRITE(*,'(/," Give the persons V̇o2max in ml/kg/min",/,
 >          " (standard=40) ",
 >          " (Enter 999 if you want to enter a relative value ",/,
 >    " (now ",F6.1,"):",\)')V̇o2max
      CALL GET(V̇o2max)
      TRAIN=(V̇o2max-20.)/40.*100.
C     vo2max=40 ml/kg min AT 50% TRAIN;
C     train=100% then 60 ml/kg min
      IF(V̇o2max.GT.100.)THEN
          WRITE(*,'(/," Give the persons training level (0-100%;",
 >                "(standard=50) ",
 >                "(now ",F6.1,"%):",\)')TRAIN
          CALL GET(TRAIN)
          V̇o2max=20.+TRAIN/100.*40.
      ENDIF
      WRITE(*,'(/," Give the number of days the person has acclimated
 >          (0-15; now ",F5.1,"):",\)')ACCL
      CALL GET(ACCLI)
C     subtract first day (see Neale, LUT 25 model)
      ACCL=ACCLI-1
      IF (ACCL.LE.0.) ACCL=0.
```

```
C     define acclimation function
      ACCLIM=1.-exp(-0.3*ACCL)
C     calculate derived parameters:
      ADU=W**.425*HEIGHT**.725*.2024
      LBM=.01*(100.-PFAT)*W
C     calculate size factors: LBM and ADU related to standard man
      XLBM=LBM/63.8
      XADU=ADU/1.965
      XW=W/75.
C     calculate specific heat
      HSPEC=.01*(PFAT*2510.+(100.-PFAT)*3650)
C     calculate fat+skin layer thickness from fat percentage and age and gender
C     BODY DENSITY (siri)
      DENSIT=(4.95/(PFAT/100.+4.5))
C     DETERMINE SSSF = SUM OF SEVEN SKINFOLDS BY ITTERATION
      SSSF=0.
      X=3.
      IF(SEX.EQ.'M') THEN
            DO WHILE (X.GT.DENSIT)
                  X=1.112-0.00043499*SSSF+0.00000055*SSSF*SSSF-0.00028826*AGE
                  SSSF=SSSF+1.
C     if quadratic function does not reach a minimum, limit SSSF to data domain in reference
                  IF(SSSF.GT.280.) THEN
                  X=DENSIT
                  WRITE(*,'(/," DENSITY IN INFINITE LOOP; STOPPED!!; any ",
 >                "key to continue",\)')
                  READ(*,'(A1)')DUM
                  ENDIF
            END DO
      ELSEIF(SEX.EQ.'F') THEN
            DO WHILE (X.GT.DENSIT)
                  X=1.097-0.00046971*SSSF+0.00000056*SSSF*SSSF-0.00012828*AGE
                  SSSF=SSSF+1.
                  IF(SSSF.GT.280.) THEN
                        X=DENSIT
                        WRITE(*,'(/," DENSITY IN INFINITE LOOP; STOPPED!!; any",
 >                      " key to continue",\)')
                        READ(*,'(A1)')DUM
                  ENDIF
            END DO
      ENDIF
C     THICKNESS SKIN+FAT = 0.5 * SSSF /7.
      FATTH=SSSF/14.
C     calculate effects of training and acclimation on sweat and bloodflow
C     limit aerobic fitness
      IF(V̇o2 max.GT.60.) THEN
            FIT= 20.
      ELSEIF(V̇o2 max.LT.20.) THEN
            FIT= -20.
      ELSE
```

```
            FIT=Vo2 max- 40.
        ENDIF
C       determine effects of acclimation and aerobic power on control functions
C       offsetsweating: effect of training, heat acclim.
        OFFSW= - FIT/10.*0.1 - acclim*0.25
C       GAIN SWEATING:
        GAINSW=(1.+FIT/20.*0.35)*(1.+acclim*0.15)
C       maximal sweat rate:
        XSWMAX=1.+acclim*0.25+FIT/20.*0.25
C       blood flow:
        OFFFL=-FIT/10.*0.1 - acclim*0.25
        GAINFL=1.
        XFLMAX=1.+acclim*0.15+FIT/60.
c
        RETURN
        END


        SUBROUTINE THREG
C
$INCLUDE: 'THINDIV0.FOR'
C       calculates physiological control according to a modified Gagge approach;
C       includes, individualization of subject response (Havenith, 1997)
        DATA TthSK,TthC,CDIL,CSTR,CSW,REGSWL,BLFLL,ALPHA
  >         /33.7,36.8,45.,.1,170.,.222,90.,.1/
C        calculate mean skin temperature from 4 skin sections (nude/clothed; yes/no radiation)
        TSKM=0.
        WSK(1)=(1.-pNUDE(K))*(1.-pRAD(K))
        WSK(2)=(1.-pNUDE(K))*pRAD(K)
        WSK(3)=pNUDE(K)*(1.-pRAD(K))
        WSK(4)=pNUDE(K)*pRAD(K)
        DO 10 I=1,4
            TSKM=TSKM+WSK(I)*TSKA(I)
10      CONTINUE
        IF(TSKM.GT.TthSK)THEN
            WARMS=TSKM-TthSK
            COLDS=0.
        ELSE
            COLDS=TthSK-TSKM
            WARMS=0.
        ENDIF
C       addition of changes in setpoint due to training and acclimation;
C       These are seperated for sweating and blood flow due to the different
C       effects of training and accli. on these parameters:
C       first for blood flow: change of WARMC in WARMCF
        IF(TC.GT.(TthC+OFFFL))THEN
C           drive from warm core for blood flow
            WARMCF=TC-(TthC+OFFFL)
        ELSE
            WARMCF=0.
```

```
      ENDIF
C     now for sweating: WARMC becomes WARMCS; as COLDC is not used
C     in bloodflow, it is calculated with the sweating offset changes.
      IF(TC.GT.(TthC+OFFSW))THEN
            WARMCS=TC-(TthC+OFFSW)
            COLDC=0.
      ELSE
            COLDC=(TthC+OFFSW)-TC
            WARMCS=0.
      ENDIF
C     removed mean body drive and replace by core and skin for more clarity:
C     TBM=ALPHA*TSKM+(1.-ALPHA)*TC
C     IF(TBM.GT.TthBM)THEN
C           WARMB=TBM-TthBM
C           COLDB=0.
C     ELSE
C           COLDB=TthBM-TBM
C           WARMB=0.
C     ENDIF
C     changes in calculations for training and acclimation effects
C     use of WARMCF and WARMCS instead of WARMC
      DILAT=CDIL*WARMCF
      STRIC=CSTR*COLDS
C     old:  SKBF=(6.3+DILAT)/(1.+STRIC)
C     a "local" warm skin effect was added (Stolwijk)
      SKBF=XADU*GAINFL*(6.3+DILAT)/(1.+STRIC)*2.0**(WARMS/6.)
      IF (SKBF.LT..5) SKBF=.5
C       Maximal flow=limit*limit change*surface factor
      FLMAX=BLFLL*XFLMAX*XADU
      IF (SKBF.GT.(FLMAX)) SKBF=FLMAX
C     old: alpha in neutral-warm varied between 0.75 and 0.95:
C     ALPHA=.042+.745/(SKBF+.59)
C     new alpha based on body resistance instaed of blood flow only, thus
C     including effect of fat and of muscle blood flow.
C
      ALPHA=0.08 + 2.*BR
      IF (ALPHA.LT.0.1) ALPHA=0.1
      IF (ALPHA.GT.0.35) ALPHA=0.35
C     remove mean body drive for more clarity; include offset shifts for
C     acclimation and training, as well as change in maximum sweat rate
C     REGSW=CSW*WARMB*EXP(WARMS/10.7)/3600.
C     adjust sweat rate for gain change due to training and acclimation and to Adu
C     REGSW=XADU*GAINSW*CSW*((WARMCS-COLDC)*(1.-ALPHA)+
C >   ALPHA*(WARMS-COLDS))*EXP(WARMS/10.7)/3600.
C     INSTEAD OF SENSITIVITY DEPENDENT ON ALPHA,
C     INTRODUCE A FIXED SENSITIVITY (CORE=12*SKIN)
      REGSW=XADU*GAINSW*(0.92*CSW*(WARMCS-COLDC)+
  >   .08*CSW*(WARMS-COLDS))*EXP(WARMS/10.7)/3600.
      IF(REGSW.LE..001)REGSW=.001
C     adjust sweat rate MAXIMUM for gain change due to training and acclimation and to Adu
```

```
      SWMAX=XADU*REGSWL*XSWMAX
      IF(REGSW.GT.SWMAX) REGSW=SWMAX
C     adjust shivering to body size (lean body mass, relative to
C     standard man:
      SHIV=19.4*COLDS*COLDC*XLBM
      IF(SHIV.GT.(225.*XLBM)) THEN
            SHIV=225.*XLBM
      ENDIF
C     metabolic rate, includes shivering:
      RM=ACT(K)+SHIV
C     respiratory heat loss
      RESP=(.0014*(34.-TA(K))+.0025*(42.-CA))*RM
C     Change heat capacity of tissue according to fat content: old:
C     HCAPSK=ALPHA*W*3500./ADU
C     HCAPC=(1.-ALPHA)*W*3500./ADU
      HCAPSK=ALPHA*W*HSPEC/ADU
      HCAPC=(1.-ALPHA)*W*HSPEC/ADU
C     body core - to -skin resistance
C     old: BR=1./(5.28+.6*1.163*SKBF)
C     Raman factor variable (see Lotens, thesis; later modified by Havenith):
      RAMAN=.25
      IF (TSKM.GT.15.) RAMAN=(TSKM-15.)*.05+.25
      IF (TSKM.GT.25.) RAMAN=(TSKM-25.)*.01+.75
      IF (RAMAN.GT..85) RAMAN=.85
C     New representation of core-to-skin resistance:
C     muscle resistance reduced by muscle blood flow as function of metabolic rate
C     reduction up to factor 5 a 10
      RMUSCLE=0.05/(1+(RM-65.)/130.)
C     fat layer resistance related to layer thickness, including skin (Veicsteinas et al)
      RFATSKIN=0.018*FATTH
C     res. blood flow as in old model
      RSKBF=1/(1.167*RAMAN*SKBF)
C     ADD RESISTANCES
C      MUSCLE + FAT
      RMUFASK=RFATSKIN+RMUSCLE
C        CORE TO SKIN
      BR=1/(1/RSKBF+1/RMUFASK)
C     calculate body heat content/gram body weight
      BHC=((TC-37.)*HCAPC+(TSKM-34.)*HCAPSK)*ADU/W*.001
      RETURN
      END
```

-Initialisation in main program:

```
      TRAIN=50.
      ACCLI=0.
      PFAT=15.
      AGE=25.
      SEX='M'
      FATTH=7.786
```

```
      OFFSW=0.
      OFFFL=0.
      GAINFL=1.
      GAINSW=1.
      XFLMAX=1.
      XSWMAX=1.
      VO2max=40.
      W=75.
      HEIGHT=1.76
      HSPEC=3500.
      LBM=(100.-PFAT)*W/100.
C     size factors
      XLBM=1.
      XADU=1.
      XW=1.
      ADU=1.96
      CRIT=.1
      SWCAPSK=2.5
```
==

Appendix 2
Bibliography

Bibliography

Publications in books and journals

Havenith G, Holewijn M (1998) *Altitude and air pollution.* In: ACSM ResourceManual for Guidelines for Exercise Testing and Prescription, 3rd edition, Williams and Wilkins publ. Accepted.

Havenith G, Coenen J, Kistemaker L, Kenney WL (1997) *The relevance of individual characteristics for human heat stress response is dependent on work intensity and climate type,* accepted by Eur J Appl Physiol.

Havenith G, Luttikholt V, Inoue Y, Kenney WL (1996) *The relevance of age for work in a warm humid climate.* In: Aging and human factors / Eds. K Brookhuis, C Weikert, J Moraal, Traffic Research Centre, 1996, p.87-91 1996 P 28

Havenith G, Heus R (1996) *Another hot summer?* Richting Sport-Gericht, 50: 269-274

Havenith G, Vuister R, Wammes LJA (1996) The effect of clothing air permeability of chemical protective clothing material on clothing vapour resistance. In: Y. Shapiro, D.S. Moran, Y. Epstein (Eds.) Environmental Ergonomics Recent Progress and new frontiers, 213-217. London and Tel Aviv: Freund Publishing House, Ltd.

Havenith G (1996) *Atlanta 1996, practical guidelines for exercise in the heat,* Geneeskunde en Sport, 29:. 16-21

Lotens WA and Havenith G (1995) *Effects of moisture absorption in clothing on the human heat balance.* Ergonomics, vol. 38: 1092-1113

Lotens WA, Havenith G, van de Linde FJG (1995) *Effects of condensation in clothing on heat transfer.* Ergonomics, vol. 38: 1114-1131

Kenney WL, Havenith G (1995) *Exercise and the environment.* The fitness Handbook, second edition, eds. Peterson and Bryant, 259-272

Havenith G, Heus R, Daanen HAM (1995) *The hand in the cold, performance and risk.* Arctic medical research, 54, suppl.2: 1-11

Havenith G, Inoue Y, Luttikholt VGM, Kenney WL (1995) *Age predicts cardiovascular, but not thermoregulatory, responses to humid heat stress.* Eur J Appl Physiol, 70: 88-97

Havenith G, Luttikholt VGM, Vrijkotte TGM (1995) *The relative influence of body characteristics on humid heat stress response.* Eur J Appl Physiol 70: 270-279

Heus R, Daanen HAM, Havenith G (1995) *Physiological criteria for functioning of hands in the cold; a review.* Applied Ergonomics, 26: 5-13

Havenith G, Vrijkotte TGM (1994) *Application of heat stress indices on military tasks.* Nederl. Milit. Geneesk. T. 47: 181-212.

Vogel JA, Rock PB, Jones BH, Havenith G (1993) *Environmental Considerations in Exercise Testing and Training.* ACSM's resource manual for Guidelines for exercise testing and prescription, Malvern: Lea & Febinger, 1993: 129-147

Kenney WL, Mikita DJ, Havenith G, Puhl SM, Crosby P (1993) *Simultaneous derivation of clothing specific heat exchange coefficients.* Med Sci Sports Exerc 283-289

Kenney WL, Havenith G (1993) *Heat stress and age: blood flow and body temperature.* J of thermal biol 18: 341-344.

Havenith G, Linde EJG van de, Heus R (1992) *Pain, thermal sensation and cooling rates of hands while touching cold materials.* Eur J Appl Physiol 65: 43-51

Lotens WA, Havenith G, editors (1992) *Proceedings of the Fifth Int. Conf. on Environmental Ergonomics,* Maastricht, November 2-6, the Netherlands

Havenith G, Middendorp H van (1990) *The relative influence of physical fitness,acclimatization state, anthropometric measures and gender on individual reactions to heat stress.* Eur J Appl Physiol 61: 419-427.

Havenith G, Heus R, Lotens WA (1990) *Clothing ventilation, vapour resistance and permeability index: changes due to posture, movement and wind.* Ergonomics 33: 989-1005

Havenith G, Heus R, Lotens WA (1990) *Resultant clothing insulation: a function of body movement, posture, wind, clothing fit and ensemble thickness.* Ergonomics 33: 67-84

Lotens WA, Havenith G (1988) *Ventilation of rainwear determined by a trace gas method.* In: Environmental Ergonomics. Mekjavics, Bannister, Morrison Eds., Taylor and Francis, Philadelphia, p. 162-175.

Havenith G (1987). *Physiological parameters in heat tolerance* (in Dutch). Nederlands Militair Geneeskundig Tijdschrift, 40: 231-233.

other publications:

Havenith G (1997) *Individual characteristics, climate, work intensity and heat stress response,* Thermal Physiology 1997, Bodil Nielsen Johannsen and Ruth Nielsen, editors, p. 31.

Havenith G (1996) *Individual differences in body core temperature response in relation to type of climate and workload.* J Sport Sci 14: 365

Havenith G, Daanen HAM (1995) *Performance effects of heat and cold.* 35th DRG Seminar on improving military performance through ergonomics, Mannheim, 20-21 September 1994, p. 251-263

Havenith G (1995) *Individual differences in body core temperature response in relation to type of climate and workload,* Int. Conf. on Dehydration, Rehydration and Exercise in the Heat, Nov 1-5, Nottingham, UK, Abstr. no. 35, page 22. Eds. Maughan, R.J. and Greenhaff, P.

Havenith G, Vrijkotte TGM (1994) *Comfort and ergonomics of gloves used by glasshouse workers.* Sixth International Conference on Environmental Ergonomics. J. Frim, M.B. Ducharme and P. Tikuisis, 25-30 September 1994, Montebello, Canada: 120-121.

Heus R, Daanen HAM, Havenith G (1994) *Dexterity, thermal comfort and pain in relation to temperature in the cold.* In: Human adaptability to work and thermal environment. First Polish-Czech International Symposium. Zakopane 28-29 March

Vrijkotte TGM, Schaapveld BCTM, Havenith G (1993). *The effect of heat stress and strain on metabolic rate during load carrying exercise.* Basic and Applied Exercise Physiology Congres, 10-11 June 1993, Nijmegen, The Netherlands

Havenith G, Inoue Y, Luttikholt VGM, Kenney WL (1993) *Combined effect of age and* $Vo_{2\,max}$ *on body temperature during work in a warm, humid climate in a heterogeneous subject population*; Proc. Thermal Physiology Symposium, IUPS

Lotens WA, Havenith G (1992). *A comprehensive clothing ensemble heat and vapour transfer model.* Proceedings of the Fifth Int. Conf. on Environmental Ergonomics, Maastricht, November 2-6, p. 74-75

Havenith G, Inoue Y, Kenney WL (1992). *The effects of age and fitness on heart rate and body heat strorage during work in a warm, humid climate.* Proceedings of the Fifth Int. Conf. on Environmental Ergonomics, November 2-6, Maastricht, p. 8-9

Kenney WL, Mikita DJ, Havenith G, Crosby P (1991) *Simultaneous Derivation of Dry and Evaporative Heat Exchange Coefficients for Military Outerwear.* 2nd Int. Symp. on clothing comfort studies in Mt. Fuji (Japan), November 30-December 2, 1991; pp 227-244

Kenney WL, Havenith G (1991) *Aging, skin blood flow, and heat tolerance.* Proc. International Conference on Human-Environment System. Tokyo, November 30-December 2, 1991); pp 87-90

Havenith G (1991). *Factors affecting clothing insulation during work.* 2nd Int. Symp. on clothing comfort studies in Mt. Fuji (Japan), November 30-December 2, 1991; pp 75-95

Havenith G (1990). *International normalization activities of ISO* (in Dutch). Symp. 'Binnenklimaat, Europese richtlijnen en normen', Utrecht, March 14

Havenith G, van Middendorp H (1989). *A quantitative model for individual heat strain.* Proceedings IUPS Symposium Thermal Physiology, Tromsø, July 17-21, p. 431-436

Havenith G, Heus R, Lotens WA (1989) *Changes in clothing heat and vapour resistance due to posture, movement and wind.* Proceedings 13th Symposium on Man-Thermal Envir. System, Sapporo, November 1-2, p. 194-197

Havenith G (1988) *Individual differences in tolerance to hot climates* (in Dutch). Proceedings Mil. Symp. "Limits to functional load", Oct. 1988, Soesterberg.

Havenith G, van Middendorp H (1986) *Prediction of the psychrometric range of a clothing system using the relation between subjective comfort votes and physiological variables.* The annals of physiological anthropology 5, 173-174

Lotens WA, Havenith G (1986). *Ventilation of garments.* The annals of physiological anthropology 5: 139-140

TNO reports

In addition, as first author, over 50 TNO company reports on research projects have been published. A list is available on request.

Acknowledgements

Acknowledgements

At this moment, finalizing this thesis, I would like to express my gratitude to several people who played an important role in my development towards this point. Firstly Maarten Woerlee and the late prof. A. Lindenmayer, for raising my interest in mathematical modelling and its application in physiology. It is a topic that I still enjoy a lot.

Next, those at TNO who taught me critical scientific thinking. I would specifically like to mention Hans Vos, who, during his time as department head, always found any remaining flaws in the reasoning in my concept-reports and challenged me to dig deeper. His position was later successfully taken over by Wouter Lotens, who continued this tradition, both as department head and later as co-promotor. Now that I have the responsibility as program manager to evaluate reports from other colleagues, I realise how difficult your task often was.

Then my promotor for this thesis, prof. R.A. Binkhorst. Rob, I enjoyed our discussions, and I am grateful that, though I already had performed a substantial part of the research presented here before contacting you, you were willing to act as my supervisor towards the completion of the thesis. Your encouragement to keep working on the thesis and withstanding and balancing the pressure of my other obligations with TNO were crucial in its finalization.

Also the TNO Human Factors Research Institute, for providing the means and the environment for doing this research. Thanks for all those who supported my work as subjects, colleagues, co-workers and support groups as instrumentation and photography.

The people at Penn State, especially Larry Kenney, for their help during my sabbatical.

Ronald, Lyda and Jeroen, for filtering incoming phonecalls and requests, during the weeks I spent in seclusion writing the last bits and pieces.

My parents, for the possibility to start a scientific career.

Marlies and Bert, thanks for staying "downstairs" in the weekends to let me work, and Ria for making "downstairs" interesting, with many trips to the zoo and playgrounds, and for all other support.

Finally I would like to thank all my friends, for their continuous tease "well, how far are you" and their critical attitude when the answer was once more "about the same distance as last time". I finally got there. You will have to find a new question.

Curriculum Vitae

Curriculum Vitae

George Havenith was born on September 25, 1956, in Heerlen (The Netherlands). After receiving his Athenaeum-B diploma at the college "Sancta Maria" in Kerkrade, he studied Biology at the State University Utrecht. He received his masters degree (cum laude) in 1983, with majors in human physiology (topic: CO_2 sensitivity of pulmonary stretch receptors) and theoretical biology (exercise parameter estimation on the computer model "MACPUF"). The work for the latter subject was in part done at McMaster University in Canada with Dr. Norman L. Jones. From 1983 to present, he is employed as scientist at TNO Human Factors Research Institute, where he became program manager of the Thermal Physiology group in 1993. During this period he spent a sabbatical year at Noll physiological research centre, Pennsylvania State University, where he worked with Dr. W. Larry Kenney, Dr. Yoshimitsu Inoue, and coworkers on aspects of ageing and heat stress. Besides his research work, he lectures on the topics of clothing physiology and occupational medicine (stress related to exercise, climate, and clothing), and participates in ISO and CEN committees on these topics. His research interests include human temperature regulation, heat and cold stress, clothing ergonomics, human performance and modelling.