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Physiological reactions to heat stress; Quantifying the effects of individual parameters

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

For the purpose of quantifying the relative influence of individual characteristics for a person's heat strain, 24 subjects were analyzed regarding their individual characteristics and exposed to three climates (21°C, 50% RH, 34°C, 80% RH and 45°C, 20% RH) with three work levels (rest, 25, and 45% $\dot{V}O_2max$). Their psychological responses were recorded and submitted to regression analysis. It was shown that 88% of the variance in heat storage could be explained by the climate and metabolism. Of the remaining variance, the %fat, the surface/mass ratio, $\dot{V}O_2max$ and sweat rate-T_{rect} gain, explained 33% of the remaining variance. 75% of the variance in heart rate was explained by metabolism and climate. Of the remaining variance, 46% was explained by the $\dot{V}O_2max$. 96% of skin temperature variation was explained by climate and metabolism. Individual parameters add only .5% to the explained variance. Prediction of T_{rect}, T_{oes}, blood pressure and skin bloodflow also improved by the addition of individual characteristics. The explained variance for these variables is too low (<70%) to use them as strain predictors, however.

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IZF 1989-30

PHYSIOLOGICAL REACTIONS TO HEAT STRESS; QUANTIFYING THE EFFECTS OF INDIVIDUAL PARAMETERS

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ABSTRACT

The importance for heat strain of inter-individual differences in fitness, state of acclimatization, hydration state, anthropometric measures, gender and age was described in a qualitative manner in many papers. The present experiment was set up to quantify the relative influence of some of these parameters on the physiological heat stress responses, in the form of regression equations. For this purpose, 12 male and 12 female subjects (group average matched for $\dot{V}O_2$max per kg fat free body weight) were first analysed regarding their individual characteristics (fitness, acclimatization state, anthropometric measures) and subsequently exposed to a neutral (21°C, 50% RH), a warm, humid (34°C, 80%RH) and a hot, dry (45°C, 20%RH) climate at three work levels (rest, 25, and 45% $\dot{V}O_2$max), seated semi-nude in a net chair behind a cycle ergometer. Their physiological responses were recorded and the dataset was then submitted to a multiple regression analysis. It was shown that 88% of the variance in *heat storage* could be explained by the climatic parameters (temperature and vapour concentration) and the internal heat production (metabolic rate). Of the remaining variance, the %fat, the surface to mass ratio, the $\dot{V}O_2$max and the sweat rate versus core temperature gain, explained together 33% of the remaining variance (total R^2=.92). The gender difference became insignificant, once %fat and surface to mass ratio were introduced in the model. 75% of the variance in *heart rate* was explained by metabolic rate and climate. Of the remaining variance, 46% was explained by the $\dot{V}O_2$max (total R^2=.88%). Inclusion of the $\dot{V}O_2$max in the model caused gender to become an insignificant factor.

96% of *skin temperature* variation was explained by climate and metabolic rate. Individual parameters (%fat, sweat gain, $\dot{V}O_2$max) add, although significant, only .5% to the explained variance. Prediction of *rectal temperature*, *oesophageal temperature*, *blood pressure* and *skin blood flow* was also shown to improve by the addition of individual characteristics. The explained variance for these variables is too low (<70%) to use them as strain predictors, however.

Finally it was shown that a simplified, reduced, set of predictors ($\dot{V}O_2$max, body surface area and the setpoint of the T_{rect}-sweat rate relation) predicts the above mentioned variables almost maximal.

-Keywords, Human factors, Heat stress, [illegible] Physiology. EMK

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Fysiologische reacties op hittebelasting: kwantificeren van de effecten van individuele parameters

G. Havenith en H. van Middendorp

SAMENVATTING

Het belang van individuele kenmerken (trainingstoestand, acclimatisatiegraad, hydratatietoestand, anthropometrische kenmerken, geslacht en leeftijd) voor de belastheid van personen tijdens hittearbeid, is in een groot aantal publicaties op een kwalitatieve wijze beschreven. De onderhavige studie is uitgevoerd om deze invloeden te kwantificeren en de relatieve invloed van de parameters te bepalen. Het resultaat van deze bewerking zijn regressievergelijkingen waarmee hittebelastheid, uitgedrukt in waarden van fysiologische variabelen, kan worden beschreven. Voor dit doel werden 12 mannelijke en 12 vrouwelijke proefpersonen (groepen geselecteerd op vergelijkbare $\dot{V}O_2max$ per kg vetvrij lichaamsgewicht) geanalyseerd op hun individuele kenmerken (getraindheid, acclimatisatiegraad, anthropometrische gegevens) en vervolgens in zwembroek/bikini blootgesteld aan een neutraal (21°C, 50% RH), een warm, vochtig (34°C, 80%RH) en een heet, droog (45°C, 20%RH) klimaat bij drie arbeidsniveaus (rust, 25 en 45% $\dot{V}O_2max$), zittend in een draadstoel achter een fietsergometer. Hun fysiologische reacties werden geregistreerd en de dataset werd vervolgens aan een multipele regressieanalyse onderworpen. Gevonden werd dat 88% van de variantie in *warmteopslag* kon worden verklaard op basis van de interne warmteproduktie (metabolisme) en het klimaat (temperatuur en dampdruk). Van de restvariantie, verklaarden het %vet, de oppervlakte-inhoud verhouding, de $\dot{V}O_2max$ en de hellingshoek van de zweetproduktie-rectaaltemperatuur relatie samen ca. 33% (totale R^2=.92). Het effect van het geslacht van de persoon verloor zijn significantie zo gauw het vetpercentage en de oppervlakte-inhoud verhouding in de vergelijking zijn opgenomen. Van de variantie in de *hartfrequentie* werd 75% verklaard door klimaat en metabolisme. Toevoegen van $\dot{V}O_2max$ verklaarde 46% van de overgebleven variantie en deed het oorspronkelijk significante effect van geslacht op de restvariantie verdwijnen.
Van de variantie in de *huidtemperatuur* werd 96% verklaard door klimaat en metabolisme. Individuele parameters (%vet, helling T_{rect}-zweetproduktie relatie) voegen, hoewel significant, slechts .5% aan de verklaarde variantie toe. De voorspelling van de *rectale-* en *slokdarmtemperatuur*, *bloeddruk* en *huiddoorbloeding* verbetert ook door toevoegen van individuele parameters. De verklaarde variantie voor deze variabelen is echter te laag (<70%) om ze als voorspeller van hittebelastheid te gebruiken.
Het bleek verder mogelijk om met een gereduceerde set van individuele parameters ($\dot{V}O_2max$, lichaamsoppervlak en de setpoint van de zweetproduktie-T_{rect} relatie) een vrijwel optimale voorspelling van bovengenoemde variabelen te geven.

1 INTRODUCTION

Physiological reactions to heat stress have been investigated and described by many authors and the results have been used for the development of thermoregulatory models (Stolwijk, 1971; Gagge, 1973; Givoni and Goldman, 1972, 1973) and for the definition of criteria for heat stress limits in work places (ISO 7243, 7933). Although these models seem to predict well for a group of workers, it has always been a problem to specify the reaction to heat stress (the strain) of an individual. Regarding the standards on heat stress limits, this has resulted in a limitation of the standards to healthy persons with physical characteristics close to the population average. In the real situation however, it is usually the part of the population which is not close to average which experiences heat stress problems. More specific: older people, overweight people, or persons with diseases affecting the heat stress response (the strain). Therefore it is very important to investigate the effects of such individual parameters on heat strain.

In several reviews of the literature dealing with heat stress (Havenith, 1985; Kenney, 1985), parameters were identified which actually influence the reaction to heat stress. This resulted in the following list, in which the parameters are presented in roughly their order of importance.

Acclimatization

A subjects state of acclimatization is of prime importance for his reaction to heat stress. With increasing acclimatization state, which can be achieved by work or training in a hot environment, the heat strain of the body will be strongly reduced, resulting in lower core temperature, heart rate etc. This is due to improved sweat characteristics (lower setpoint, higher gain, better distribution and efficiency) and circulation (expanded plasma volume, better flow distribution, lower drop in blood pressure).

Physical fitness

The core temperature reached during work is roughly proportional to the ratio of metabolic energy expenditure and the individuals maximal oxygen uptake, i.e. the relative workload or $\%\dot{V}O_2max$. Improving physical fitness has a beneficial effect on cardiopulmonary performance. Further, fitness is often confounded with acclimatization as training can result in an improvement of the acclimatization state.

Anthropometric measures

Differences in body size and body composition between subjects affect thermoregulation through their effect on the physical process of heat exchange (higher insulation and lower heat capacity of fat tissue, surface to mass ratio) and through differences in the amount of passive weight (fat) which subjects have to carry. Further, several effects directly related to obesity have been shown. However, these are probably due to confounding of obesity with physical fitness or other parameters, resulting in higher resting and work heart rate, cardiac enlargement, alveolar hypoventilation and diminished skin blood flow.

Hydration state

A subjects hydration state will influence his thermoregulation through the influence of plasma volume on circulatory capacity and of plasma osmolality and specific ion (Na^+, Ca^{++}) concentration on sweat gland and brain function.

Drugs and alcohol

Drug abuse, including alcoholism, may predispose individuals to excessive heat strain by physiologically or behaviourally altered thermoregulation. Few data are available on this subject. Minard (1980) listed potentially harmful drugs, including diuretics, anticholinergic drugs, vasodilators, antihistamines, atropine, tranquilizers and sedatives, Beta- blockers and amphetamines. Especially the Beta-blockers deserve attention as large numbers of workers take this type of drug for treatment of hypertension and other cardiovascular diseases. It has been shown that heat tolerance decreases due to this drug. The underlying mechanisms may vary with the specific drug.

Hypertension

Hypertensive subjects differ from normotensive subjects in their heat stress response, having a lower cardiac output and skin blood flow on one hand but a higher evaporative rate on the other. This results in similar heart rate and core temperature responses for both groups. Thus a direct effect of hypertension on heat tolerance has not been shown. However, a vast majority of diagnosed hypertensives takes some type of antihypertension medicine, which reduces their heat tolerance.

Time of day

Body temperature fluctuates with the time of day, as do setpoints for thermoregulatory actions like sweating. The effect on heat tolerance is yet unclear, but the effect on test results should be considered.

Sex

The parameter sex is of little importance for thermoregulation since effects, usually described to gender, appear to be confounded with differences in fitness, acclimatization and anthropometric measures.

Age

Similarly to the parameter sex, the effects found with increasing age are for a large part confounded with other parameters. Remaining differences may be explained by changes in the skin structure.

Although the effects of these parameters have been qualitatively described in numerous publications, few data are available on their quantitative effects. For this purpose the present study was performed, attempting to relate the physiological reactions to heat stress tests to a number of the above mentioned parameters.

When an attempt is made to quantify the effects of these parameters it is often a problem to define the parameter in a measurable way. Of course this is no problem with sex, age, time of day and anthropometric measures. With hydration state, physical fitness and especially the state of acclimatization, however, several aspects have to be distinguished for each parameter, which are not necessarily highly correlated. In a pilot study on the effects of acclimatization and fitness (Havenith, 1986), it was suggested to define fitness in terms of maximal oxygen uptake (absolute or related to fat free body mass) and to define the state of acclimatization by the setpoint and gain of the sweat rate-core temperature relation (supplemented by the additional heart rate due to heat). The interaction between fitness and acclimatization state which was described in that study will thus not be treated separately but instead be attributed to the main effects fitness and acclimatization. Hydration state could be defined in terms of plasma volume and osmolality.

The idea of the current experiment is to gather data on physiological responses to heat stress for a range of subjects with different characteristics regarding the above mentioned parameters and to subject these data to a statistical analysis in order to determine the relative importance of each parameter. As the investigation of all parameters at once would increase the size of the experiment too much, it was decided to vary only a limited number of parameters within the investigated group, trying to keep the others constant. The parameters which were attempted to keep constant in the experiment are: hydration, time of day, the health status and age. This was achieved by replenishment of all fluid losses, experimenting during morning only, checking health through questionnaires and subject selection, respectively. Thus the parameters which show variations are: acclimatization, fitness, anthropometric measures and sex.

Two climates with similar cooling power according to the WBGT index (WBGT ±31.5°C) were chosen for the heat stress tests: hot dry (45°C, 20% RH) and warm humid (34°C, 80% RH). Further, an identical test is performed under neutral to cool conditions, to determine the specific effects of heat, opposed to the effects of work.

2 METHODS

Twenty-four subjects were selected for the test, twelve males and twelve females. They were informed of the test procedures and risks, after which they signed an informed consent. It was attempted to balance the groups of males and females regarding their fitness, expressed in maximal oxygen uptake per kg fatfree body weight (Fig. 1).

Before the test series, the subjects performed an incremental exercise test up to submaximal levels in which the relation between heart rate and oxygen uptake was determined. For the determination of the maximal oxygen uptake ($\dot{V}O_2max$) this relation was extrapolated up to the maximal heart rate which was estimated (Åstrand and Rodahl, 1973) as:

$$HRmax = 210 - .65 * Age \qquad (bpm) \qquad (1)$$

The subjects were weighed and their height was measured. From these data their body surface area was determined (Dubois and Dubois, 1916) by:

$$BSA = 71.84 * 10^{-4} * height^{.725} * weight^{.425} \qquad (m^2) \qquad (2)$$

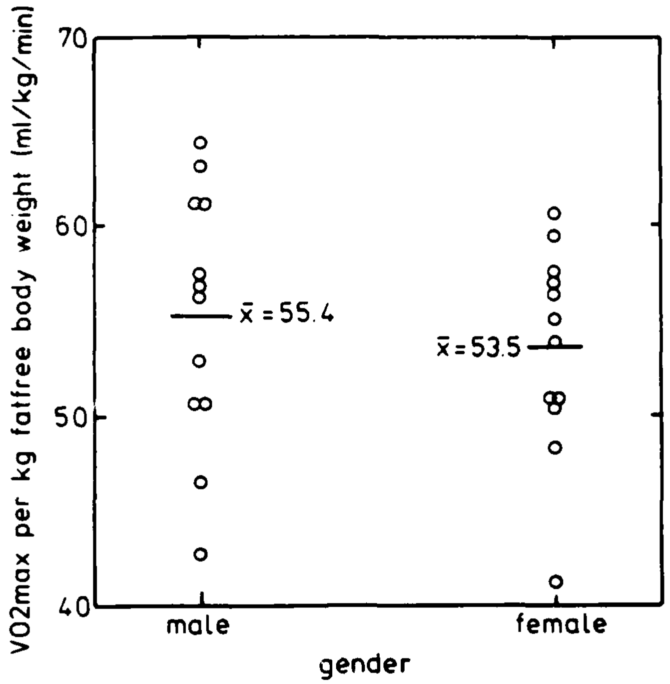

Fig. 1 Distribution of maximal oxygen uptakes (in ml/kg fat free body mass) over the groups of males and females.

Table I Anthropometric and functional data of the test subjects.

subj.	sex	age	height (cm)	weight (kg)	BSA (m^2)	%fat (%)	$\dot{V}O_2$max (l/min)	$\dot{V}O_2$max* (ml/min kg) (fatfree)
1	M	24	186	72.08	1.96	16.4	2.80	46.47
2	M	27	182	85.87	2.07	23.0	3.50	52.93
3	M	24	181	65.14	1.84	14.9	3.15	56.82
4	M	26	189	67.33	1.92	18.2	3.55	64.46
5	M	23	177	69.09	1.85	15.1	3.30	56.26
6	M	23	188	79.44	2.05	15.8	3.85	57.56
7	M	25	183	68.99	1.89	15.5	3.57	61.24
8	M	26	181	63.29	1.81	12.6	2.80	50.62
9	M	27	193	82.15	2.12	19.5	3.35	50.66
10	M	21	182	68.13	1.88	13.8	3.60	61.30
11	M	28	184	84.03	2.07	16.4	3.00	42.71
12	M	24	187	77.12	2.03	16.9	4.05	63.20
13	F	24	171	65.88	1.77	23.7	3.05	60.68
14	F	21	183	77.20	1.99	30.0	2.98	55.14
15	F	23	176	61.12	1.75	22.8	2.69	57.01
16	F	22	167	67.72	1.77	26.8	2.95	59.51
17	F	24	176	63.41	1.78	31.2	2.35	53.87
18	F	20	170	75.58	1.87	32.0	2.90	56.43
19	F	21	172	70.67	1.84	35.4	2.30	50.38
20	F	24	179	70.26	1.88	29.2	2.05	41.21
21	F	27	167	69.27	1.78	30.0	2.47	50.94
22	F	21	174	79.38	1.94	36.6	2.43	48.28
23	F	28	159	54.95	1.56	27.4	2.30	57.65
24	F	21	167	57.44	1.64	29.2	2.07	50.90

The amount of body fat was determined by measuring the skinfold thickness with a calliper gauge at four sites: biceps, triceps, suprailiacal and subscapular, and consequent calculation of the fat percentage using the relation between skinfold thickness and body fat determined by Durnin et al (1967, 1974). The anthropometric and functional data of the subjects are listed in Table I.

Of all subjects the relation between sweat rate and rectal temperature (T_{rect}) was determined in a hot, dry climate (45°C, 20%) to ensure that all produced sweat evaporated. By changing the work rate, three equilibrium values for sweat rate at steady state rectal temperatures were determined. These three datapoints were connected by a linear regression line, from which the slope of the relation and the T_{rect} setpoint for the onset of sweating were determined (Fig. 2).

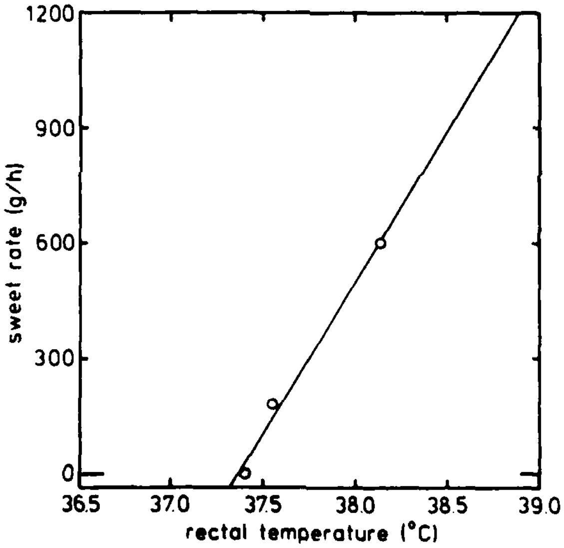

Fig. 2 Determination of the setpoint and gain of the sweat rate versus T_{rect} relation based on measurements at three work levels in a hot, dry climate.

The experimental protocol included three tests on each subject: a control test in a cool environment (21°C, 50% RH) and two heat stress tests. One heat stress test was performed in a warm humid climate (34°C, 80% RH, WBGT 31.9°C), the other in a hot dry climate (45°C, 20% RH, WBGT 31.4°C). The tests were performed on separate days, with one or two days in between. The order of the tests was balanced over the subjects.

Each of the three tests was identical except for the climate. The subjects were dressed in shoes, slip and, the females, bra. During the test the subject was seated in a wire chair behind an electronically controlled bicycle ergometer (modified Monark) in a reclining position. The wire chair was chosen to cover as little body surface as possible (Fig. 3). The test was split up in three periods of 30 minutes each. In the first period the subjects rested in the chair, in the second they cycled with a work load chosen to demand an oxygen uptake of 25 %$\dot{V}O_2$max and in the third period they worked at 45%$\dot{V}O_2$max. It was chosen to let the subjects work at a load relative to their work capacity instead of a fixed load.

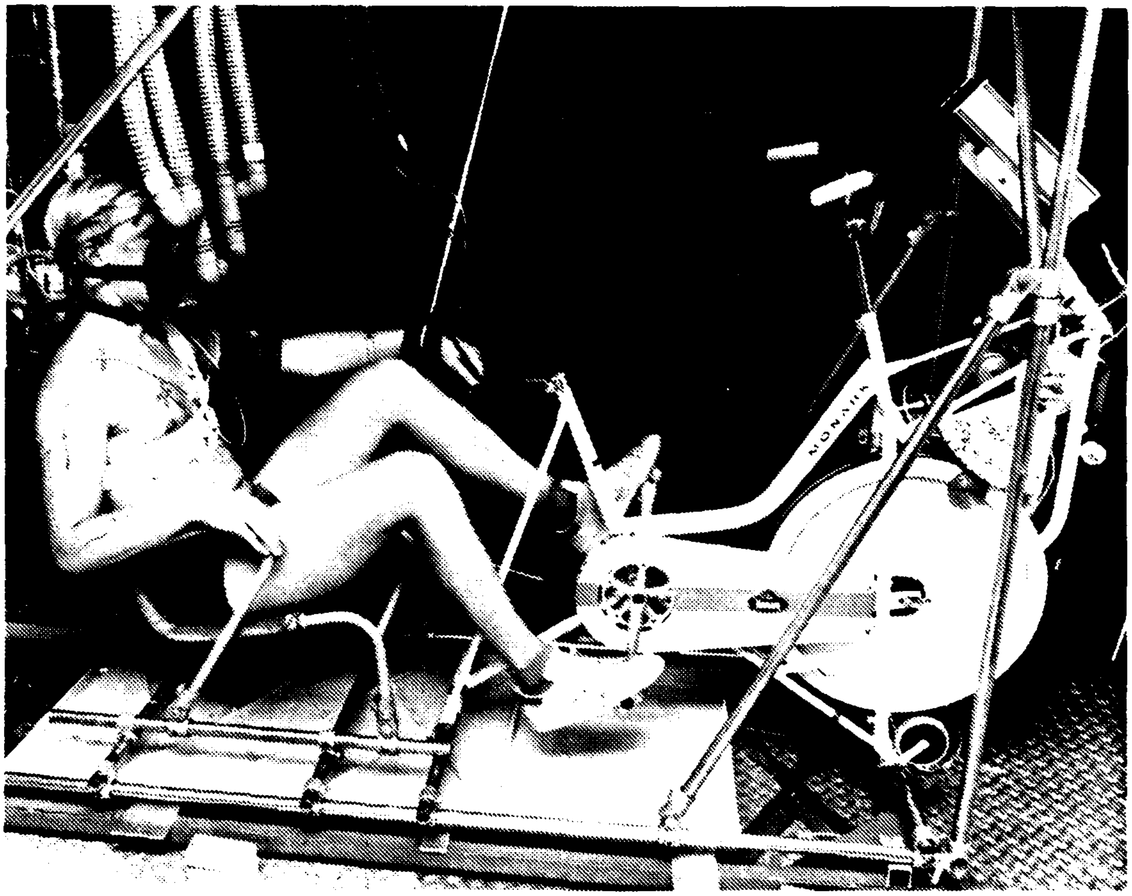

Fig. 3 The experimental setup.

The subjects oxygen uptake was measured with a custom build closed oxygen system (Fig. 4). The subject in- and exhaled air which circulated in a tubing system. Expired carbondioxide was absorbed by sodalime. The oxygen concentration in the system was measured (Servomex, polarographic oxygen analyzer) and regulated using a valve, which injected oxygen into the system through a calibrated gas meter. The amount of oxygen which had to be injected to maintain a constant oxygen concentration is equal to the oxygen uptake of the subject.

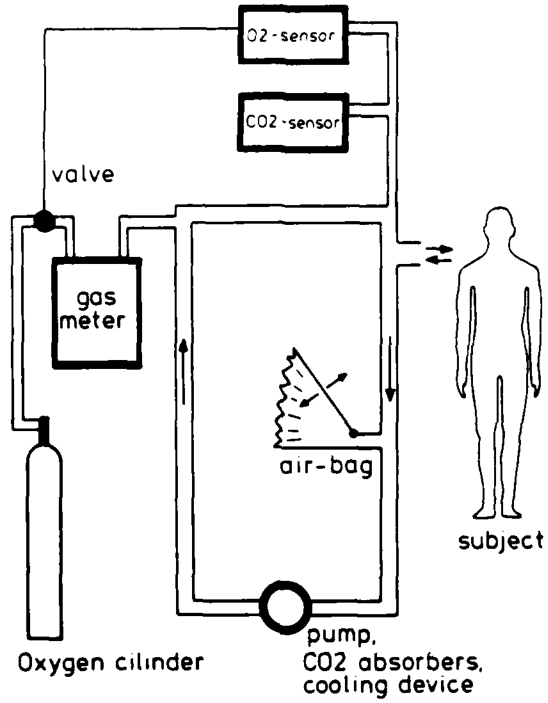

Fig. 4 Schematic diagram of the closed oxygen system.

The ECG was continuously monitored, from which heart rate was deducted and recorded.

Body core temperatures were recorded:
- by a rectal probe, inserted to 12 cm beyond the anal sphincter (YSI-700 linear thermistor) and
- by a thermocouple, inserted in the oesophagus down to the level of the right atrium (about 37-40 cm from the nose). During the insertion of the thermocouple probe (2 mm), the mucous membranes of the nose were locally anaesthetized with Xylocaine spray and gel.

Skin temperature was determined at 7 sites on the body (Fig. 5). Average skin temperature was calculated from these 7 separate measurements, weighted for the surface area they represent.

$$T_{sk} = .07\,T_{head} + .175\,(T_{chest} + T_{back}) + .07\,T_{upperarm} + .12\,T_{lowerarm} + .19\,T_{upperleg} + .20\,T_{lowerleg} \quad (^{\circ}C) \qquad (3)$$

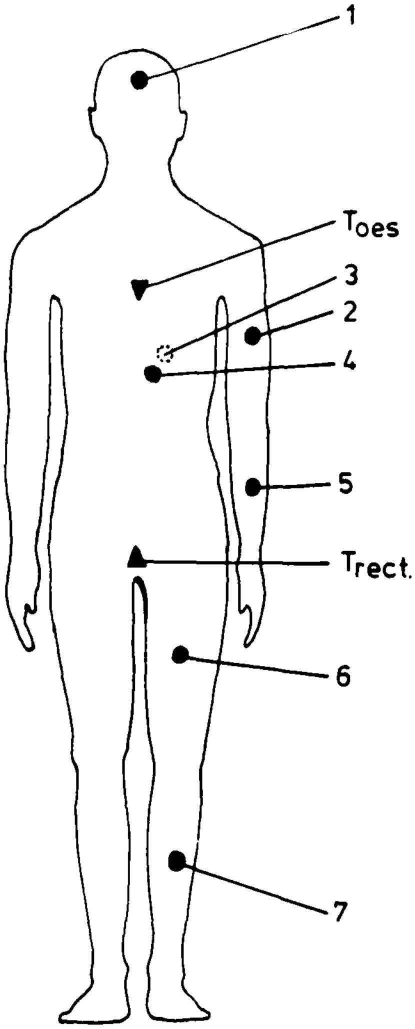

Fig. 5 Placement of temperature sensors.

Heat storage was calculated by a weighted sum of rectal and skin temperature deviations from fixed values of 37 and 33°C respectively:

$$\text{Storage} = 3.48\ [.8(T_{rect}-37) + .2(T_{sk}-33)] \qquad (J/g) \qquad (4)$$

with: 3.48 = heat capacity of body tissue (J/g°C)

Forearm blood flow, representing skin blood flow (Edholm et al., 1956; Roddie et al., 1956) was determined twice every three minutes by strain gauge plethysmography (Whitney, 1953). The wrist of the subject rested in a sling, which held the arm at shoulder level. The mercury in silastic strain gauges were mounted around the lower arm. A pressure cuff was mounted around the wrist, which was periodically inflated to above 200 mm HG, thus closing all arterial blood flow to and from the hand. Another cuff was mounted around the upper arm, which was at the same time inflated to just above venous pressure. So, blood could enter the arm but not leave it. The inflow of blood to the arm could be determined through the volume registration.

Systolic, diastolic and mean blood pressure were measured 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 setup was mounted on a scale, which determined weight changes with an accuracy of ca. 10 grams. Dripping sweat was collected in a basin filled with paraffine oil, mounted on the scale underneath the subject. The sweat which drips of the subject will disappear beneath the surface of the paraffine oil and thus will not evaporate. All weight change except the metabolic components, can therefore be attributed to sweat actually evaporated from the subject.

Before and after each session the subjects were weighed for the determination of the total sweat loss.

All data, except the blood flow measurements were collected every second, averaged over a minute and recorded by a PDP-11/03 and 11/23 computer system. For the analysis, the values at the end of each 30 min. period were used, as these usually approached steady state values.

The statistical analysis was done using the statistical software package "SYSTAT".

In the regression analysis, the parameters which were independent of the individual (e.g. ambient temperature, vapour pressure, work rate) were, if relevant, introduced first. Then, a certain residual variance is still left, which has to be explained by the individual differences between the subjects. Next, these individual parameters were introduced into the equation. The order in which this was done was determined by the level of their correlation with the residual variance. When this correlation was similar for more parameters, the choice for a parameter was based on the ease of its determination, however. When for example body mass and the gain of the sweat rate - T_{rect} relation had similar correlations with the residual variance in the data set, the much easier to determine body mass would be introduced first. Further it was chosen not to exclude extreme datapoints from the analysis in advance, as these points might reflect typical individual characteristics.

3 RESULTS

The observed ranges of all variables in the experiment are presented in Table II.

Table II Ranges of the variables.

	abbreviation	minimum	maximum	mean	sd
ambient temperature (°C)	T_a	21	45	33.5	9.8
ambient vapour pressure (kPa)	pH_2O	1.24	4.5	2.5	1.35
external work rate (W)	W_{ext}	0	115	33.3	35.5
body mass (kg)	mass	54.95	85.87	70.65	7.96
body length (m)	length	1.59	1.93	1.78	.08
body surface area (m^2)	BSA	1.56	2.12	1.88	.14
Surface/mass ratio (m^2/kg)	surfmass	.024	.029	.027	.001
body fat percentage (%)	%fat	12.6	36.6	23.0	7.33
Maximal oxygen uptake (l/min)	$\dot{V}O_2$max	2.05	4.05	2.96	0.55
$\dot{V}O_2$max per kg body weight (ml/min/kg)	$\dot{V}O_2$kg	29.2	52.8	42.0	6.9
$\dot{V}O_2$max per kg fat free body weight (ml/min/kg)	$\dot{V}O_2$kgff	41.2	64.5	54.4	6.0
Setpoint sweating(°C)	Setp	36.6	38.4	37.6	.5
Gain sweating(g/s°C)	gain	.074	.333	.172	.073
rectal temperature (°C)	T_{rect}	36.60	38.84	37.57	0.43
oesophageal temperature (°C)	T_{oes}	37.15	39.73	37.98	0.53
average skin temperature (°C)	T_{sk}	27.35	39.20	34.12	3.68
body heat storage (J/g)	Store	-5.05	9.13	2.37	3.14
heart rate (bpm)	HR	48	161	102	29
oxygen uptake (l/min)	O_2	.250	1.800	.812	.441
metabolic rate (kW)	Metab	.085	.612	.276	.150
systolic blood pressure (mm HG)	Syst	72	257	126	28
diastolic blood pressure (mm HG)	Diast	39	132	65	16
mean blood pressure (mm HG)	meanbp	53	157	83	18
forearm blood flow (ml/100ml/min)	FBF	.4	33.0	7.1	6.6
sweat rate (g/hr)	sweat	10	1248	252	279

3.1 *Heat storage*

Increasing heat storage shows that the physiological reactions to the heat stress are insufficient to remove all the excess heat from the body. This can imply that too little heat dissipates from the body surface by dry heat loss and/or evaporation, or that the circulation is unable to transport sufficient heat from the core to the skin. Thinking of a model description which predicts the accumulation of heat in the body, three parameters are obvious. The first concerns the heat production in the body, the energy expenditure or metabolic rate. The other two define the heat dissipation from the body to the environment: the ambient temperature (Dry heat loss) and water vapour pressure (Evaporative heat loss).

Relating the heat storage data over all experimental conditions with these parameters, it appears that metabolic rate, metabolic heat production (metabolic rate - external work rate) (both in Watts) and water vapour pressure show a relatively low correlation (R=.24 and .41 respectively), whereas the ambient temperature shows a high correlation (R=.89). It is important to realize that the low correlation for the water vapour pressure does not imply that it has little effect on the body heat storage. An explanation is that the choice of ambient temperatures is such that the vapour effect is confounded in a larger temperature effect. Thus, the vapour effect will only become visible once the temperature effect is taken account of, respectively when both parameters are entered into the prediction simultaneously.

Building a descriptive model of the parameters, important for the heat storage, it is obvious that climate should be introduced first. The regression equation is:

$$\text{Store} = -7.7 + .271\ T_a + .398\ pH_2O \qquad (R=.91) \qquad (5)$$

Entering the metabolic rate shows:

$$\text{Store} = -9.04 + .27\ T_a + .404\ pH_2O + 4.88\ \text{metab} \qquad (R=.94) \qquad (6)$$

Or using the heat production instead of metabolic rate:

$$\text{Store} = -9.17 + 6.124\ \text{heat prod.} + .27\ T_a + .405\ pH_2O \qquad (R=.94) \qquad (7)$$

Thus, these basic parameters are able to explain 88% (R^2) of the variance in the heat storage data.

Table III Correlation coefficients of individual parameters with the residual variance in heat storage after application of equation 6 (n=216).

anthropometric data:					
LENGTH	-0.331	MASS	-0.393	SURFMASS	0.272
BSA	-0.406	%FAT	0.340		
fitness:					
%$\dot{V}O_2MAX$	0.131	$\dot{V}O_2MAX$	-0.320	$\dot{V}O_2KG$	-0.122
$\dot{V}O_2KGFF$	0.094				
acclimatization:					
SETPOINT	0.464	GAIN	-0.324		
others:					
SEX	0.398				

The next step in the analysis is to investigate how much of the remaining variance (12%) can be explained by the individual characteristics of the subject and how much must be attributed to experimental noise. For this purpose the residual variance which is left after applying equation 6, is correlated with the individual parameters of the subjects. The results are given in Table III.

The squared values of these coefficients give the percentage explained variance in the residue based on a single parameter description model. It can be seen that the anthropometric data, the gender, the sweat characteristics and the fitness data still show a correlation with the residual variance in the data. As the anthropometric data are the most simple to determine, it was chosen to investigate their influence first. Introducing the body weight, length, fat percentage, body surface area and the surface to mass ratio, in order of their significance (correlation recalculated after addition of each parameter), the body surface area is entered first, followed by the fat percentage. These two explain 21% of the residual variance. The length and mass add further to the explained variance, bringing the total up to 30%. Taking instead of the body surface area the surface to mass ratio, together with the fat percentage, these two parameters explain 27% of the residual variance, which is higher than the first two parameters in the stepwise approach. The other anthropometric parameters do not add significantly to the explained variance, once these two have been entered in the equation. The complete equation is given as equation 8 in Table IV.

Table IV Regression coefficients for the regression on body heat storage with environmental, heat production and individual parameters. R^2 represents the total explained variance by the equation; R^{2*} represents the percentage of the residual variance left after application of equation 6, which is explained by individual parameters.

Eq	Constant	T_a °C	PH_2O kPa	Metab kW	%fat %	Surf/Mass m2/kg	$\dot{V}O_2max$ l/min	Gain g/s°C	R^2	R^{2*}
6	-9.0	.27	.40	4.88					.88	0
8	-19.6	.27	.40	5.68	.071	326.6			.91	21
9	-22.6	.27	.40	5.55	.093	383.1	.359		.92	29
10	-21.3	.27	.40	5.38	.096	342.8	.468	-3.2	.92	33

Another parameter which does not contribute any more after the parameters in equation 8 have been entered, is the subjects gender. Of the other possible parameters, both fitness and sweat characteristics still show some correlation. Of the different fitness descriptors ($\dot{V}O_2$max absolute, per kg body weight, per kg fat free body weight), the absolute value in l/min. gives the best addition, which results in equation 10 in Table IV.

These additions (%fat, surfmass, $\dot{V}O_2$max) explain 29% of the residual variance of equation 6.

When adding the sweat characteristics, both the gain and setpoint of the sweat rate t_{core} relation add significantly to the equation, while the setpoint does not add significantly when both are entered (equation 10 in Table IV). For the residual variance this addition leads to 33% explained variance. This is not visible in the total R^2 due to truncation.

Older work by Åstrand (1960) and Saltin and Hermansen (1966) suggests 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. The climate should only show 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. As was found in the data analysis, the effect of relative work rate indeed is a good predictor, when used together with the climatic parameters. Then 90% is explained of the total variance, which is the same as when adding both absolute metabolic rate and $\dot{V}O_2$max. Discarding the climatic variables, the relative work rate explains only 7% of the heat storage.

Summarizing, the analysis showed that individual parameters explain one third of the variance in heat storage, which is left after the climatic and metabolic parameters are entered in the prediction. The relevant parameters are: fat percentage, body surface area or surface to mass ratio, maximal oxygen uptake and the gain of the sweat rate - T_{rect} relation.

3.2 *Heart rate*

The second parameter which is commonly used as heat strain indicator is the heart rate. The heart rate reflects the transport activity of oxygen and metabolic fuel to the tissues and is augmented by the need for heat transport from the body core to the skin. Thus, in the heat, heart rate is bound to be higher than in neutral or cool environments.

The approach used for the construction of a predictive model of heart rate is equal to the approach for heat storage. First the climatic and

metabolic parameters are introduced and then the individual characteristics.
This results in the following models:

$$\text{Heart rate} = 59.15+.157\ \text{metab} \qquad (R=.82) \qquad (11)$$

and

$$\text{Heart rate} = 30.6 + 156.5\ \text{metab} + .80\ T_a + .78\ pH_2O \qquad (R=.87) \qquad (12)$$

This analysis of the heart rate data (equation 12) shows that 75% of the heart rate variability can be explained by the ambient temperature and the metabolic rate. The next step is again to take the residual 25% of the variance and to correlate it to the individual parameters. This results in the correlation coefficients presented in Table V.

Table V Correlation coefficients of individual parameters with the residual variance in heart rate after climate and metabolic rate are entered in the equation (n=216).

anthropometric data:					
LENGTH	-0.457	MASS	-0.366	SURFMASS	0.175
BSA	-0.459	%FAT	0.451		
fitness:					
$\%\dot{V}O_2MAX$	0.284	$\dot{V}O_2MAX$	-0.682	$\dot{V}O_2KG$	-0.511
$\dot{V}O_2KGFATFREE$	-0.381				
acclimatization:					
SETPOINT	0.548	GAIN	-0.176		
others:					
SEX	0.485				

The subjects maximal oxygen uptake appears to show the highest correlation with the residual 25% of the variance. Of this residual variance the parameter $\dot{V}O_2$max is able to explain 46% as can be seen in Table VI in which the equations are given. Adding $\dot{V}O_2$max brings the total explained variance of heart rate to 88%. The next step, addition of the sweating setpoint as acclimatization parameter, does, although significant, hardly increase the explained variance any further.

Table VI Regression coefficients for the regression on heart rate with environmental, heat production and individual parameters. R^2 represents the total explained variance by the equation; R^{2*} represents the percentage of the residual variance left after application of equation 12, which is explained by individual parameters.

Eq	Constant	T_a °C	PH_2O kPa	Metab kW	$\dot{V}O_2max$ l/min	Setpoint °C	R^2	R^{2*}
12	30.6	.80	.78	156.5			.75	.0
13	82.0	.79	.76	175.3	-19.0		.88	.46
14	-159.9	.78	.98	173.7	-16.1	6.2	.88	.49

As now both metabolic rate and $\dot{V}O_2max$ are in the equation it is now interesting to investigate their replacement in equation 13 by expressing the work load as $\%\dot{V}O_2max$. It was shown that this increases the explained variance to 89%:

$$\text{Heart rate} = 23.3 + .78\ T_a + .77\ pH_2O + 1.84\ \%\dot{V}O_2max \quad (R=.94) \qquad (15)$$

Addition of more parameters (setpoint), although significant does not raise the explained variance by more than .3%.

A different approach of heart rate prediction, is to regard the heart rate in relation to its two tasks of oxygen transport to the tissues and heat transport to the skin. In this approach, the metabolic rate again reflects the need for oxygen and/or heat production, whereas the need for heat transport to the skin is given by the heat accumulation in the body: the heat storage. This results in:

$$\text{Heart rate} = 55.95 + .141\ \text{metab} + 3.191\ \text{store} \quad (R=.89) \qquad (16)$$

The residual variance (21%) must, similar to the first approach, be due in part to inter-individual differences and in part to experimental noise (the heat storage, which is entered in the model, already contains a certain amount of the individual differences). Analyzing the residual variance with a single parameter model (Table VII) shows that the maximal oxygen uptake is the best predictor, which explains up to 42% of the variance in the residue.

Table VII Correlation coefficients of individual parameters with the residual variance in heart rate after metabolic rate and body heat storage are entered in the equation (n=216).

anthropometric data:					
LENGTH	-0.406	MASS	-0.292	SURFMASS	0.118
BSA	-0.389	%FAT	0.398		
fitness:					
%$\dot{V}O_2$MAX	0.272	$\dot{V}O_2$MAX	-0.651	$\dot{V}O_2$KG	-0.522
$\dot{V}O_2$KGFATFREE	-0.441				
acclimatization:					
SETPOINT	0.467	GAIN	-0.104		
others:					
SEX	0.420				

Addition of more parameters (fat percentage and setpoint of the sweat rate versus core temperature relation) increases the explained variance of the residue by only 2% to 44%, bringing the total explained variance to 88% (Table VIII).

Table VIII Regression coefficients for the regression on heart rate with heat production, heat storage and individual parameters. R^2 represents the total explained variance by the equation; R^{2*} represents the percentage of the residual variance left after application of equation 16, which is explained by individual parameters.

Eq	Constant	Metab kW	Store J/g	$\dot{V}O_2$max l/min	%Fat %	Setpoint °C	R^2	R^{2*}
16	55.9	140.9	3.2				.79	.00
17	102.4	159.7	2.8	-17.1			.88	.42
18	-55.5	158.6	2.8	-17.8	-.29	4.4	.88	.44

The conclusion of this paragraph is that the major individual parameter in the determination of heart rate is the individuals fitness level, expressed as his maximal oxygen uptake. The fitness level can best be used to express the work rate relative to the maximal work rate (%$\dot{V}O_2$max).

The other contributing parameters are the setpoint of the sweat rate - T_{rect} relation (acclimatization), and the fat percentage.

3.3 *Core temperature*

Instead of using the body heat storage as an indicator of heat strain, in the ISO documents on heat strain (ISO DP 9886) the basic parameters core and skin temperature are considered separately. Therefore, these two variables were also investigated separately in this study.

Two indicators for body core temperature were measured in this study: rectal temperature and oesophageal temperature. The determination of the latter was problematic in about one third of the subjects. Thus the data set for it is considerably smaller. For the rectal temperature, 38% of the variance could be explained by the climate together with the metabolic rate. The equation becomes:

$$T_{rect} = 36.71 + .013\ T_a - .002\ pH_2O + 1.55\ \text{metab} \qquad (R=.62) \qquad (19)$$

The correlation of the residual variance with the individual characteristics is shown in Table IX.

Table IX Correlation coefficients of individual parameters with the residual variance in rectal temperature, when metabolic rate and ambient temperature and vapour pressure are entered in the equation (n=216).

Anthropometric data:					
LENGTH	-0.358	MASS	-0.329	SURFMASS	0.174
BSA	-0.376	%FAT	0.452		
fitness:					
$\%\dot{V}O_2MAX$	0.155	$\dot{V}O_2MAX$	-0.395	$\dot{V}O_2KG$	-0.236
$\dot{V}O_2KGFATFREE$	-0.024				
acclimatization:					
SETPOINT	0.515	GAIN	-0.258		
others:					
SEX	0.497				

Of the residual variance, about 37% could be explained by individual characteristics as the setpoint of the sweat rate versus T_{core} relation, maximal oxygen uptake, fat percentage and surface to mass ratio.

The complete equation:

$$T_{rect} = 26.16 + .012T_a + -.004\ pH_2O + 1.736\ \text{metab} + .026\ \%\text{fat} + 82.29\ \text{surfmass} + .108\ \dot{V}O_2\text{max} + .197\ \text{setpoint} \qquad (R=.77) \qquad (20)$$

explains 60% of the variance.

For the oesophageal temperature, the ambient temperature, vapour pressure and the metabolic rate explain together 56% of the variance:

$$T_{oes} = 36.64 + .023\ T_a - .022\ pH_2O + 2.098\ metab \qquad (R=.75) \qquad (21)$$

The fat percentage and the setpoint of the sweat equation together explain 35% of the residual variance. This brings the total explained variance to 71% with the equation:

$$T_{oes} = 27.68 + .024\ T_a - .017\ pH_2O + 2.274\ metab + .015\ \%fat + .23\ setpoint \qquad (R=.84) \qquad (22)$$

Summarizing, the most important individual parameters for the core temperature prediction are: setpoint of the sweat rate - T_{rect} equation, fat percentage, surface to mass ratio, and the maximal oxygen uptake.

3.4 *Skin temperature*

Skin temperature prediction is done similar to the other body temperatures. The ambient temperature, vapour pressure and metabolic rate explain 96% of the variance in skin temperature:

$$T_{sk} = 21.20 + .336\ T_a + .588\ pH_2O + .827\ metab \qquad (R=.98) \qquad (23)$$

it appeared that this could only slightly be improved by addition of the maximal oxygen uptake, the body fat percentage and the sweat gain. As this improvement is less than .5% in explained variance it is regarded as irrelevant. The data for T_{sk} thus seem to show little dependence on individual parameters.

3.5 *Blood pressure*

Regarding systolic blood pressure, only 45% of the variance can be explained. The parameters in the model are: ambient temperature and humidity, maximal oxygen uptake, body surface area and setpoint of the sweat function. The climatic and metabolic parameters explain 39% of the variance:

$$\text{Systolic bp} = 177.4 - 1.4\ T_a - 5.4\ pH_2O + 34.0\ metab \qquad (R=.63) \qquad (24)$$

the individual parameters explain 14% of the residue. The complete equation then becomes:

$$\text{Systolic bp} = 676.2 - 1.4\ T_a - 5.4\ pH_2O + 25.3\ \text{metab} + 14.5\ \dot{V}O_2\text{max} - 60.1\ \text{BSA} - 11.3\ \text{setpoint} \qquad (R=.69) \qquad (25)$$

Taking only the physiological parameters (thus without ambient temperature and vapour pressure) the explained variance amounts to only 39%. This is similar for diastolic and mean blood pressure.
The complete equations are:

$$\text{Diastolic bp} = 119.7 - .77\ T_a - 3.2\ pH_2O - 13.4\ \text{metab} + 9.5\ \dot{V}O_2\text{max} - 27.2\ \text{BSA} + 40.6\ \text{gain} \qquad (R=.69) \qquad (26)$$

$$\text{Mean bp} = 147.1 - .89\ T_a - 3.6\ pH_2O - 4.5\ \text{metab} + 10.9\ \dot{V}O_2\text{max} - 33.3\ \text{BSA} + 38.5\ \text{gain} \qquad (R=.70) \qquad (27)$$

3.6 *Skin blood flow*

Skin blood flow prediction based on the climate and the metabolic rate results in the following equation which gives an explained variance of 54%:

$$\text{skin blood flow} = -11.8 + .37\ T_a + .62\ pH_2O + 18.7\ \text{metab} \qquad (R=.73) \qquad (28)$$

of the individual parameters only the gain of the sweat rate - T_{rect} relation is of importance:

$$\text{skin blood flow} = -9.2 + .36\ T_a + .61\ pH_2O + 18.4\ \text{metab} - 14.2\ \text{gain} \qquad (R=.76) \qquad (29)$$

Taking physiological parameters instead of the climatic results in an explained variance of 51%:

$$\text{skin blood flow} = -217.5 + 5.1\ T_{rect} + .9\ T_{sk} + 1.54\ \dot{V}O_2\text{max} - 7.66\ \text{gain} \qquad (R=.72) \qquad (30)$$

Apparently the sweat gain is the most relevant individual parameter.

4 DISCUSSION

An impression of the remaining discrepancy between the prediction equations and the actual data is produced by Fig. 6-10, where the predicted values are plotted against the actual data points. Ideally, all points should lie on the line of identity. It can be seen that the prediction for body heat storage and heart rate (Fig. 6 and 7) is a very good one. Over the whole range of data, the prediction agrees well, even for the negative values of body heat storage (body cooling). Predicting rectal temperature (Fig. 8) appears to be more difficult. The remaining deviations in the data are still quite large. Fig. 9 shows the skin temperature prediction results. It is apparent, that here the choice of the climatic parameters has clustered the dataset. Nevertheless, the predictions are quite reasonable over the relatively large (10°C) range of observed skin temperatures. The prediction of skin blood flow (Fig. 10) appears the least accurate of the discussed predictions. The curved relation between prediction and actual data suggests that a non-linear approach might be more suitable for this data set. The attempts which were made to analyze the data with non-linear regression have not yet produced improved prediction results, however.

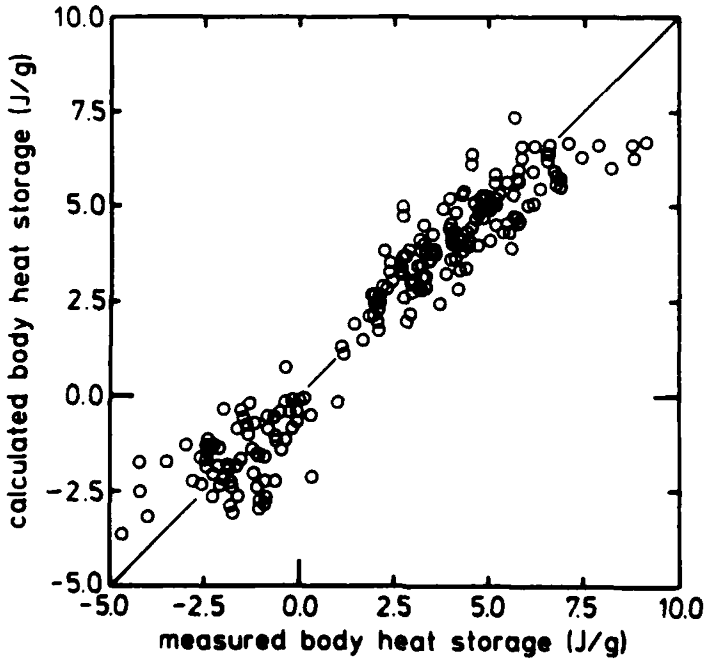

Fig. 6 Heat storage values calculated using the regression equation in relation to measured heat storage data.

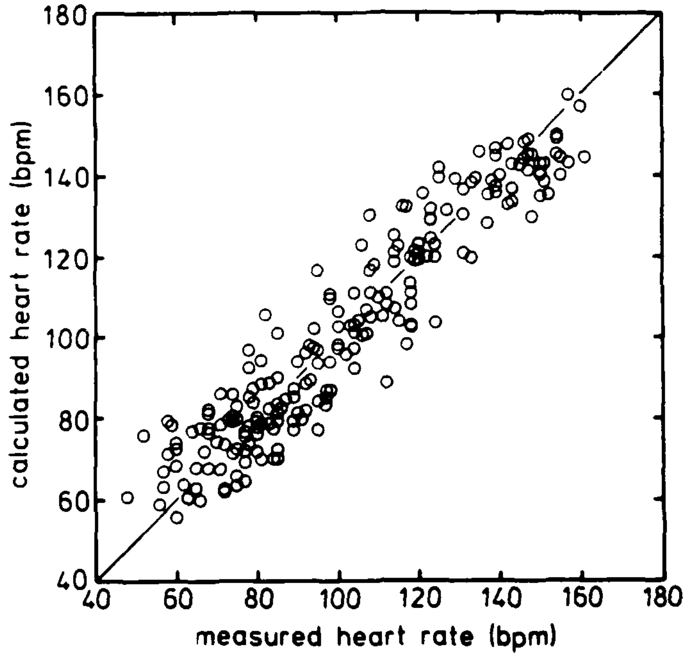

Fig. 7 Heart rate values calculated using the regression equation in relation to measured heart rate data.

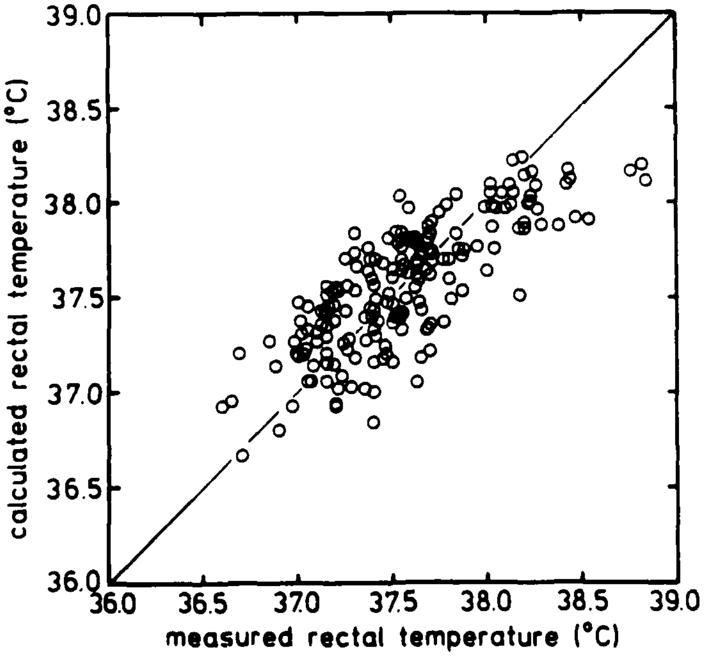

Fig. 8 Rectal temperature values calculated using the regression equation in relation to measured rectal temperature data.

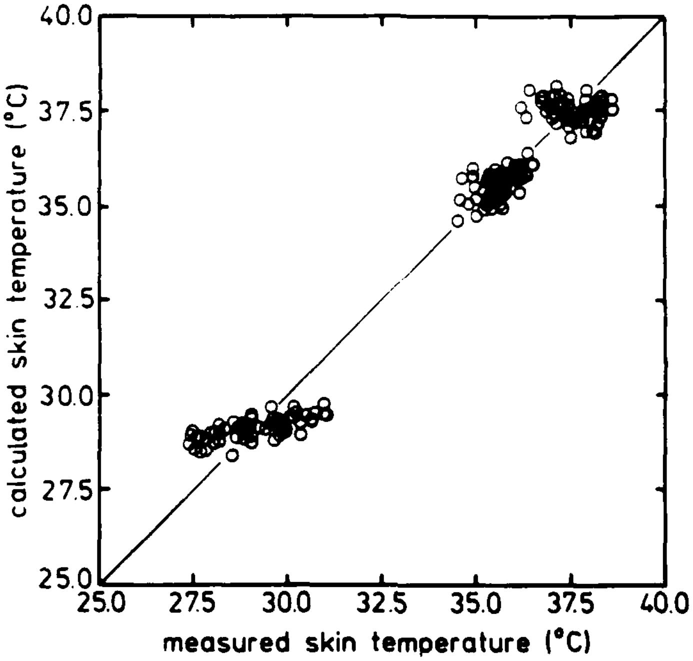

Fig. 9 Skin temperature values calculated using the regression equation in relation to measured skin temperature data.

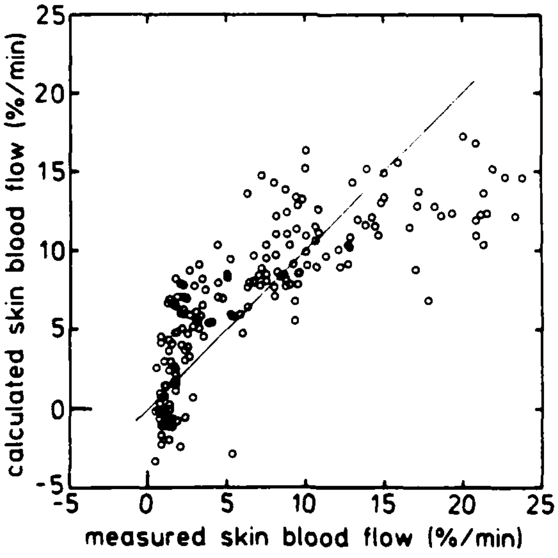

Fig. 10 Skin blood flow values calculated using the regression equation in relation to measured skin blood flow data.

Whenever body heat content is discussed, a problem is whether one defines relative to a fixed body temperature or to the initial value (measured in the rest situation). For a resting person the initial temperature follows the circadian rhythm. Thus the deviation from this resting value should be physiologically the most relevant variable. The regression equation for the heat storage defined as the change from the resting value is:

$$\text{Storage}' = -1.17 + .03\ T_a + .1\ pH_2O + 5.38\ \text{metab} - .18\ \dot{V}O_2\text{max} - 2.2\ \text{gain} \qquad (R=.80) \qquad (31)$$

However, in the statistical analysis we found that the other approach, the deviation from an absolute value, showed much higher correlations with the relevant parameters (total R^2 92% vs. 64%) . One conclusion which may be drawn from these findings is that the resting values we determined are not representative of the setpoint values. Apparently one has to define the circumstances in which a subject starts his tests more accurately then was done in this experiment, in order to understand the results better. Another possibility is that the heat strain is defined by the absolute heat content instead of the change in heat content. Based on these findings, the analysis of heat storage was therefore related to heat storage as the deviation from a fixed heat storage at a core temperature of 37 degrees and a skin temperature of 33 degrees.

Few is published regarding heat storage prediction. The model described in the present experiment shows that a reasonable (R^2=88%) prediction of heat storage is possible, based on metabolic rate or metabolic heat production and the environmental parameters temperature and vapour pressure. It was chosen to use metabolic rate instead of metabolic heat production in the further analysis of heat storage, as the latter did not show a higher predictive value both in this experiment and in literature (Nielsen, 1966), and as the metabolic rate is a more simple parameter.

Equation 11 in Table IV shows that the inter-individual differences explain a significant part of the remaining variance. In agreement with the conclusions made by Havenith (1985) based on a review of literature, the important individual characteristics appear to be the sweat rate - core temperature relation, the fitness and the anthropometric data of the subject. A combination of these parameters explained one third of the remaining variance, bringing the total to 92%. A problem is of course that some of these parameters are confounded in the data set (fat people usually also have a low surface to mass ratio) so that each parameter separately may add substantially to the explained variance, but that a combination of parameters hardly adds more than a single one.

The prediction of <u>heart rate</u> using climatic parameters and metabolic rate with individual parameters showed a similar amount of explained variance as when the body heat storage was used instead of the climate.

In the prediction equation (16), the body heat storage, as indicator for the need to pump blood to the skin to cool, produced better results than when the actual core temperature was used. In the storage term, skin temperature is represented also, which may be an indicator of the effectiveness of the heart in the heat transport to the skin.

Another interesting point is to replace the body heat storage by the values of both core and skin temperature. This results in:

$$\text{Heart rate} = -310.97 + 1.68\ \%\dot{V}O_2\text{max} + 8.02\ T_{rect} + 1.93\ T_{sk} \quad (R=.95) \quad (32)$$

The weighting function of core and skin temperature for the heart rate response appears to be very similar to the one described in literature for the calculation of the average body temperature (80 versus 20%, Houdas and Sauvage, 1971).

Regarding the individual parameters influencing the heart rate, it was expected (Havenith, 1985) that the subjects fitness would be a major contributor to the subjects heart rate, as by improving fitness the oxygen consumption - heart rate relation is improved and the thermal effect on circulation is reduced. The strong effect of fitness was indeed observed. It was found that putting the percentage of $\dot{V}O_2$max into the equation instead of metabolic rate and $\dot{V}O_2$max, improved the explained variance slightly. Apparently the latter parameter holds more information on the subjects heat tolerance.

An effect of the body fat percentage was expected, as this was described by a number of authors (Burse, 1979; Buskirk et al., 1971; Haymes et al., 1975). However it was suggested (Havenith, 1985) that part of the results observed by the mentioned authors might be attributed to the fitness differences between the subjects for two reasons. The first is that their fitness is often confounded with their fat content. The second is that in the heat the insulating fat layer does not necessarily form an additional hindrance to heat dissipation from the body core (Burse, 1979), being by-passed by the blood flow. Thus it was expected that after correction for fitness, the effect of fat percentage would be absent or very small. In the present experiment, the effect indeed appears to be absent, after the individual parameter fitness is introduced.

The additional effect of the setpoint of the sweat rate function can be seen as a contribution from the acclimatization status of the subject.

Prediction of heart rate response to heat exposure was attempted earlier by Vogt et al. (1973), Givoni and Goldman (1973) and van de Linde et al. (1982). However, they did not include the individual characteristics of the subjects. Givoni and Goldman studied clothed subjects and included the clothing in the equation, which makes comparison difficult. Vogt et al. found in an experiment with four nude adults a relationship of: $HR = HR_{rest} + .4\ W_{ext} + 18\ T_{rect} + 3\ T_{sk} - 765$. For a group of subjects, HR_{rest} can be included in the constant term. The similar equation in this study would be: $HR = .526\ W_{ext} + 18\ T_{rect} + 1.62\ T_{sk} - 647$. Thus we observe similar gains for the external work and rectal temperature, but a lower gain for the skin temperature influence. The latter may well be due to the larger range of skin temperatures in this study, compared to Vogt et al.'s. Van de Linde et al. attempted to predict the metabolic rate based on measurements of heart rate, core and skin temperature. Although the parameters in their equation are the same, it is statistically not allowed to rewrite their equation for metabolic rate based on heart rate and body temperature into one for heart rate based on metabolic rate and body temperature. Reanalysing our data to create a similar equation to theirs produced different results: a lower gain for heart rate and T_{sk} and an insignificant contribution of T_{rect}.

For the rectal temperature prediction, the best predicting parameters are similar to those for the body heat storage: climate, metabolic rate, $\dot{V}O_2max$, fat percentage, surface to mass ratio and setpoint of the sweat rate function. The total explained variance (60%) is smaller than the one for body heat storage or the similar average body temperature (92%). In other words the body heat storage correlates better with the parameters under investigation than the body core temperature. This is similar for the oesophageal temperature,of which 71% of the variance can be explained, be it on a smaller data set.

The prediction of skin temperature has been studied by a number of authors. The interest in skin temperature lies in its strong relation with comfort sensation and the consequent use in comfort prediction models (ISO 7730). As was shown, T_a was the major parameter in the T_{sk} prediction ($R^2=.92$). This was similar in earlier studies. Regarding the constant and the slope of the equations derived by the different experimentators, it can be seen that both are dependent on the domain of the data on which the equations were based (Fig. 11). Meyer (1981) gives a separate equation for rest and for exercise for temperatures above 34°C: rest: $T_{sk} = 29 + .15\ T_a$; work: $T_{sk} = 31.5 + .11\ T_a$. Mairiaux et al. (1987) found: $T_{sk} = 30 + .149\ T_a$ ($R^2=.77$) with data from ambient temperatures of 23 and 50°C. At the lower temperatures their subjects performed work, preventing the subjects from cooling (Tsk range 32.7-38.4°C). Missenard (1973) reported constants between 19.5 and 23.5 and slopes of .35 to .45 with T_a ranging from 10 to 35°C. In yet another study, Saltin et al. (1972) with T_a values of 10 to 40°C, found $T_{sk} = 27 + .22\ T_a$. This study showed $T_{sk} = 22.2 + .358\ T_a$, including both rest and work sessions at temperatures between 21 and 45°C. The overall idea is that when low ambient temperatures and rest sessions are included in the data set, allowing low skin temperatures, the constant of the equation will be lower and the gain higher. Thus, the sensitivity of skin temperature for ambient temperature reduces when ambient temperature increases. This can be seen in relation to the thermoregulatory mechanisms. Letting the skin cool down is not really a problem for the body for a wide range of skin temperature, as redistribution of the blood flow protects the body core from cooling too far. Heating up the skin above core temperature is however not acceptable as then the body core loses all cooling capacity to the skin and from there to the environment. Thus keeping skin temperature below core temperature has high priority.

The ambient vapour pressure is mainly relevant in warm conditions when sweat cooling is necessary. Thus the observed positive influence of ambient vapour pressure on skin temperature was expected. The coefficient for pH_2O (in the regression equation that also includes T_a) is in this study larger (.587) than the one observed by Mairiaux et al. (1987) of .25, which may however be attributed to the difference in the domain of the data, as was seen earlier for the coefficient of T_a.

The addition of more parameters in the T_{sk} description was hardly relevant, as the contribution to the explained variance was, although significant, less than .5%. Mairiaux et al. (1987) found significant contributions of metabolic rate, clothing insulation, wind speed and rectal temperature, but these added no more than 2% to an R^2 of 81% (in this study the R^2 was already 96%). They did not investigate individual characteristics.

One characteristic of the current data set for skin temperature is that the choice of the combinations of air temperature and vapour pressure used may have introduced the initial high correlation with T_a and pH_2O. The low residue then may give too little variation for the analysis of other parameters. The parameters which do give a small, but significant contribution: metabolic rate, fat percentage, maximal oxygen uptake and sweat gain, represent the heat loss and production mechanisms, the fitness and the acclimatization state.

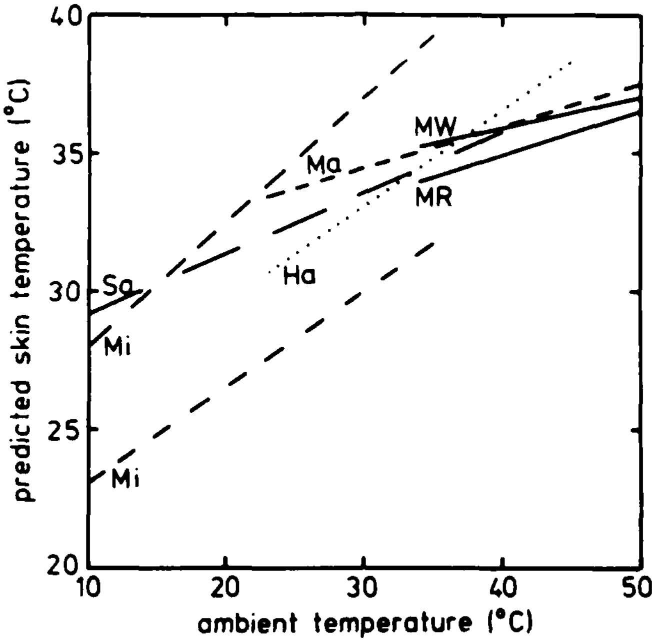

Fig. 11 Regression equations for skin temperature prediction based on ambient temperature as found in literature and the present experiment. Abbreviations: MW: Meyer (1981), work; MR: Meyer (1981), rest; Ma: Mairiaux et al. (1987); Mi: Missenard (1973); Sa: Saltin et al. (1972); Ha: this study.

Blood pressure is often monitored in relation to heat strain. However, it is difficult to measure heat strain by measuring blood pressure, as they do not correlate well. Only when heat strain limits are reached, blood pressure reflects this occurrence: the blood pressure collapses, as does the subject. Prediction of blood pressure is difficult. The explained variance for the blood pressure prediction and the skin blood flow prediction (47 and 57%) remains relatively low, compared to the value for the previously described variables. The effect of inter-individual differences could be shown for both variables, however. In general, it can be said that the explained variance for these two variables is too low to use them as strain predictors.

For the influence of the subjects gender on the presented results, the hypothesis was (Havenith, 1985) that although the subjects were reasonably matched by fitness (per fat free body mass), still an effect would be present as there was also a difference in fat content, surface area etc.. The second hypothesis was however, that this effect would vanish when the other individual characteristics as fat percentage, surface area etc. were incorporated in the analysis. It was shown in the analysis, that indeed a considerable effect of gender was present in the data, but also that for all the discussed variables this effect disappeared after entering the fat percentage and surface to mass ratio, for some variables augmented with the absolute $\dot{V}O_2max$ and the sweat gain or setpoint. The presently used method provides similar results as the method of Avellini and Kamon (1980) and Frye et al. (1981, 1982) who succeeded to eliminate the effect of gender by explicitly matching their groups of subjects by fitness and by body composition. Often, the results for the different genders presented in literature only became equal after an acclimation regime (Avellini and Kamon (1980). In this experiment, this was not necessary.

Is it possible to summarize the results of this study, producing prediction equations based on the same set of predictors? For this purpose we have to look at all the prediction equations and determine the most quoted parameters. The inclusion of the climatic parameters seems obvious, as is for most variables the inclusion of the metabolic rate as determinant for heat production. Of the individual parameters, the maximal oxygen uptake is present in most predictions, and of the anthropometric data, the body surface area is the most frequent parameter, whereas the body fat percentage and surface to mass ratio are present less often. Of the sweat characteristics, the setpoint seems to have a slightly bigger influence than the gain. The suggested individual parameters for inclusion into the equations are therefore the maximal oxygen uptake, the body surface area, and finally the setpoint for the core temperature-sweat rate relation. The results of this related analysis are given in Table X.

Table X Regression coefficients for the investigated variables in relation to a limited set of parameters. R^2 = explained variance; R'^2 = explained variance for best equation (see results).

Parameter:	n	Constant	T_a (°C)	PH_2O (kPa)	Metab (kW)	$\dot{V}O_2max$ (l/min)	BSA (m2)	Setpoint (°C)	R^2	R'^2
Variable:										
Storage	189	-39.4	.267	.403	5.466	n.s.	-1.59	.664	.91	.92
Heart rate	189	-159.9	.777	.975.	173.746	-16.055	n.s.	6.195	.88	.88
Trect	189	24.9	.012	-.004.	1.719	n.s.	-.407	.332	.54	.60
Toes	135	26.8	.024	-.018.	2.308	-.133	n.s.	.271	.70	.71
Tsk	216	23.4	.336	.589	.758	.347	-1.746	n.s.	.97	.97
Syst BP	187	676.2	-1.402	-5.415	25.342	14.463	-60.134	-11.293	.48	.48
Diast BP	187	385.9	-.774	-3.208	-13.584	7.827	-30.030	-6.612	.46	.47
Mean BP	187	435.0	-.885	-3.608	n.s.	8.754	-37.099	-7.139	.47	.47
Skin bl.fl	189	-73.3	.358	.604	18.750	n.s.	n.s.	1.636	.58	.57

The results show that a prediction based on a limited number of parameters is indeed possible without a significant loss of explained variance, except for rectal temperature, where fat% and/or the surface to mass ratio appear to be better predictors than now introduced. The most remarkable change is that $\dot{V}O_2max$ is not a significant parameter in the storage prediction. Inspection showed that with the other individual parameters included, $\dot{V}O_2max$ is only significant when entered together with the body fat percentage. As the latter is excluded, $\dot{V}O_2max$ is insignificant.

5 CONCLUSION

It was shown that heat strain prediction, operationalized by prediction of body heat storage and heart rate, can be improved when the inter-individual differences between subjects are considered in addition to the climate and the internal heat production. Once the climatic and heat production data are introduced in the different models, the individual parameters are able to explain 33 to 49% of the residual variance.

Further, it was shown that, instead of matching groups of subjects for a parameter in order to correct for its influence, as is usually done in literature, it is also possible to quantify the effect of such a parameter. Then the correction for the effect of this parameter can still be made. The parameters which add to the explained variance represent the anthropometry of the subject (fat percentage, surface area or surface to mass ratio), his fitness ($\dot{V}O_2max$) or his acclimatization state (fitness together with the sweat rate - T_{core} relation). A simplified set of parameters, uniform for all predictions, that predicts almost maximal, includes $\dot{V}O_2max$, body surface area and the setpoint of the sweating relation.

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