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# Sweating in extreme environments: heat loss, heat adaptation, body-fluid distribution and thermal strain

Nigel Taylor

*University of Wollongong*, [ntaylor@uow.edu.au](mailto:ntaylor@uow.edu.au)

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# Sweating in extreme environments: heat loss, heat adaptation, body-fluid distribution and thermal strain

## **Abstract**

Evaporation is an extremely powerful cooling process. When totally evaporated from the skin surface, sweat can remove body heat at a rate of  $2.43 \text{ kJ} \cdot \text{g}^{-1}$ . Humans therefore control sweat secretion to maintain thermal homeostasis. Since humans are capable of extended sweat rates approximating  $30 \text{ g} \cdot \text{min}^{-1}$ , it is possible to remove heat at rates  $>73 \text{ kJ} \cdot \text{min}^{-1}$ . Assuming a 20% efficiency, such heat loss will support a normothermic total energy use of 1520W. This equates with an external work rate of 304W, eliciting an oxygen consumption  $>3.5 \text{ l} \cdot \text{min}^{-1}$ . However, while man has a great capacity to both work and dissipate metabolically-derived heat, exercise under various environmental extremes may impede heat dissipation. Under such conditions, the cumulative effects of metabolic and environmental thermal loads may represent an uncompensable heat stress, predisposing to hyperthermia.

## **Keywords**

body, adaptation, loss, heat, environments, distribution, extreme, strain, sweating, thermal, fluid

## **Disciplines**

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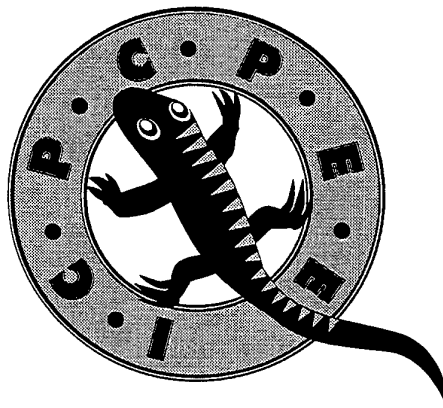
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# Table of Contents

INVITED LECTURE 1: EXERCISE, HEAT STRESS AND FATIGUE	
M. Hargreaves .....	1
PAPER 1: THE INFLUENCE OF WHOLE BODY VS TORSO PRE-COOLING ON PHYSIOLOGICAL STRAIN AND PERFORMANCE OF HIGH INTENSITY EXERCISE IN THE HEAT.	
G.G. Sleivert, J.D. Cotter, W.S. Roberts and M.A. Febbraio .....	4
PAPER 2: THE INFLUENCE OF TORSO AND WHOLE-BODY PRE-COOLING ON STRAIN AND PERFORMANCE DURING ENDURANCE WORK IN THE HEAT.	
J.D. Cotter, G.G. Sleivert, W.S. Roberts and M.A. Febbraio .....	8
INVITED LECTURE 2: HEAT STRESS AND EXERCISE METABOLISM	
M.A. Febbraio .....	12
PAPER 3: EFFECT OF ENVIRONMENTAL TEMPERATURE ON STEADY-STATE AND MAXIMAL CYCLING	
J.P. Finn, J.F. Marsden, R.J. Wood and A.L. Travar.....	17
INVITED LECTURE 3: HYDRATION EFFECTS ON THERMOREGULATION AND PERFORMANCE IN THE HEAT	
M.N. Sawka.....	21
PAPER 4: THE EFFECT OF GLYCEROL HYPERHYDRATION ON OLYMPIC DISTANCE TRIATHLON PERFORMANCE IN HIGH THERMAL STRESS.	
A. Coutts, P. Reaburn and K. Mummery .....	24
PAPER 5: THE MAIN FUNCTION OF THERMOREGULATION AND THE SUBJECT OF TEMPERATURE CONTROL	
K.P. Ivanov.....	28
INVITED LECTURE 4: SWEATING IN EXTREME ENVIRONMENTS: HEAT LOSS, HEAT ADAPTATION, BODY-FLUID DISTRIBUTION AND THERMAL STRAIN.	
N.A.S. Taylor. ....	32
PAPER 6: TO WHAT EXTENT DOES THERMAL SENSATION REFLECT PHYSIOLOGICAL HEAT STRAIN	
S. Baker, and J. Grice.....	36
PAPER 7: THERMAL SWEATING FOLLOWING SPINAL CORD INJURY.	
B.R. Wilsmore, J.D. Cotter, A.D. MacDonald, A. Zeyl, G. Bashford, and N.A.S. Taylor. ....	39
INVITED LECTURE 5: PARTICIPATION OF GASTROINTESTINAL ENDOTOXINS IN THE TOLERANCE OF HEAT AND EXERCISE	
J.R.S. Hales and S. Sakurada .....	42
PAPER 8: PREVENTION AND TREATMENT OF AN EXPERIMENTAL HEAT STROKE MODEL.	
M-T Lin.....	45
PAPER 9: INTER-RELATIONSHIPS BETWEEN SWEATING, CORE AND INTRAMUSCULAR TEMPERATURES.	
G. Russell, D.P.Y. Koonen, T. Heemskerk, D. Hennekens, H. Groeller and N.A.S. Taylor. ....	48
INVITED LECTURE 6: TIME COURSE OF HEAT ACCLIMATION AND ITS RETENTION	
K.B. Pandolf.....	51

PAPER 10: URINALYSES AND BODY MASS CHANGES DURING AN ULTRA-DISTANCE ENDURANCE EVENT: THE SIMPSON DESERT CYCLE CHALLENGE P. Reaburn and A. Coutts .....	56
INVITED LECTURE 7: HUMAN HEAT ACCLIMATION: WHAT IS THE BEST METHOD? R. Withey .....	60
PAPER 11: THE THERMOREGULATORY STRAIN PRODUCED BY PROTECTIVE PVC SUITS DURING SIMULATED CHEMICAL SPILL CLEAN-UP OPERATIONS IN A HOT ENVIRONMENT IS NOT REDUCED BY PASSIVE COOLING VESTS. R. Holdsworth and M. Crowe .....	61
PAPER 12: ENHANCEMENT OF PERFORMANCE THROUGH HEAT ACCLIMATION AND RACE SIMULATION AMONGST MOTORSPORT ATHLETES S.M. Walker, B. Dawson and T.R. Ackland.....	65
INVITED LECTURE 8: THE IMPORTANCE OF AEROBIC FITNESS IN DETERMINING TOLERANCE TO UNCOMPENSABLE HEAT STRESS T.M. McLellan .....	68
PAPER 13: THE EFFECTS OF WEARING SUNSCREEN LOTION ON THERMOREGULATORY RESPONSES DURING EXERCISE IN THE HEAT IN ADULT AND ADOLESCENT MALES. G. Naughton, J. Carlson, M. Gibbs and R. Snow .....	72
PAPER 14: WHOLE-BODY PRE-COOLING: THERMAL, CARDIOVASCULAR AND METABOLIC CONSEQUENCES. A.D. MacDonald, J. Booth, A.L. Fogarty, K.A. Armstrong, H. Groeller, A. Hahn, L.H. Storlien and N.A.S. Taylor. ....	76
PAPER 15: ENHANCED CUTANEOUS BLOOD FLOW AND HEAT OF SORPTION AFTER THE ONSET OF SWEATING DURING HEAT LOAD K. Tanaka and K. Hirata .....	80
INVITED LECTURE 9: NUTRITIONAL NEEDS IN THE HEAT L. Burke .....	83
PAPER 16: EXERCISE NORTHERN AWAKENING: NUTRITION STUDY C. Booth, R. Coad, C. Forbes-Ewan, G. Thomson, P. Davies and P. Niro .....	86
PAPER 17: DO CAFFEINE AND EPHEDRINE HAVE A BENEFICIAL IMPACT ON HUMAN PERFORMANCE DURING PROLONGED EXPOSURE TO A COLD, WET AND WINDY ENVIRONMENT? A.S. Weller, E.M. O'Connor, V.R. Nevola, and M.H. Harrison .....	89
INVITED LECTURE 10: AN EVALUATION OF THE CONCEPT OF LIVING AT MODERATE ALTITUDE AND TRAINING NEAR SEA LEVEL A.G. Hahn, C.J. Gore, D.T. Martin, M.J. Ashenden, A.D. Roberts and P.A. Logan.	92
PAPER 18: CLOTHING INSULATION AND THERMAL COMFORT OF TENT OCCUPANTS AT HIGH ALTITUDE K. Cena and P. Tapsell .....	98
PAPER 19: EFFECTS OF COLD ON MANUAL PERFORMANCE IN SUBJECTS WITH RAYNAUD'S PHENOMENON S. Rissanen, J. Hassi, K. Juopperi and H. Rintamäki.....	102
INVITED LECTURE 11: EXERTION-INDUCED FATIGUE AND THERMOREGULATION IN THE COLD A.J. Young and J.W. Castellani .....	105

<b>PAPER 20: RELATIONSHIP BETWEEN MANUAL PERFORMANCE, EXTREMITY TEMPERATURES, AND RATE OF BODY HEAT STORAGE DURING COLD EXPOSURE</b>	
M.B. Ducharme, D. Brajkovic and J. Frim .....	109
<b>PAPER 21: THE EFFECTS OF WIND ON THERMAL RESPONSES DURING LIGHT AND MODERATE EXERCISE IN THE COLD</b>	
T. Mäkinen, D. Gavhed, I. Holmér, H. Rintamäki .....	112
<b>PAPER 22: EVIDENCE OF SHIVERING FATIGUE: VERIFICATION OF A PREDICTION MODEL</b>	
P. Tikuisis, D.A. Eyolfson, X. Xu, and G.G. Giesbrecht.....	115
<b>INVITED LECTURE 12: PSYCHOPHYSIOLOGICAL ASPECTS OF COGNITION: TOWARDS AN UNDERSTANDING OF PERFORMANCE IN EXTREME ENVIRONMENTS</b>	
R.J. Barry .....	118
<b>PAPER 23: ANS AND CNS EFFECTS OF LIMB IMMERSION IN ICE COLD WATER</b>	
R.D. O'Donohue, R.J. Barry and B.P. Corless.....	122
<b>PAPER 24: HEART RATE VARIABILITY AS A MEASURE OF COGNITIVE WORKLOAD</b>	
D. Foran, M. Skinner and S. Smith.....	126
<b>PAPER 25: PSYCHOMETRIC ASSESSMENT OF THE EFFECTS OF THERMAL STRAIN ON COGNITION</b>	
C. Hocking, R. Silberstein, W.M. Lau, W. Roberts, C. Stough and D. Amos.....	130
<b>INVITED LECTURE 13: MARKSMANSHIP AND SENTRY DUTY PERFORMANCE UNDER EXTREME ENVIRONMENTS</b>	
R.F. Johnson.....	133
<b>PAPER 26: COGNITIVE PERFORMANCE AND PHYSICAL STRESSORS IN EXTREME ENVIRONMENTS</b>	
R. Brandeis.....	137
<b>PAPER 27: BRAIN ELECTRICAL ACTIVITY MAPPING AND THE EFFECTS OF THERMAL STRAIN ON A SPATIAL WORKING MEMORY TASK</b>	
C. Hocking, R. Silberstein, W.M. Lau, W. Roberts, C. Stough and D. Amos.....	141
<b>INVITED LECTURE 14: THE MEASUREMENT OF THERMAL STRAIN IN SOLDIERS OPERATING IN NORTHERN AUSTRALIA</b>	
D. Amos .....	144
<b>PAPER 28: THERMAL STRESS AND PERSONAL COOLING SYSTEM</b>	
P. Bandopadhyay, W.M. Lau and D. Amos .....	152
<b>PAPER 29: EVALUATION ON THE COOLING SYSTEMS OF AIRTIGHT SUITS USED IN THE CLOSED ECOLOGY EXPERIMENTAL FACILITIES</b>	
N. Kakitsuba, N. Watanabe and Y. Shirane.....	155
<b>INVITED LECTURE 15: PREDICTIVE MODELING: ITS USE IN FORECASTING HUMAN RESPONSES TO THE ENVIRONMENT</b>	
R.R. Gonzalez.....	159
<b>PAPER 30: THE CONTRIBUTION OF SOLAR RADIATION TO HEAT STRESS AND HEAT STRAIN DURING WORK IN ENCAPSULATING PROTECTIVE SUITS</b>	
S.E. Atkinson and G.V. Coles.....	163
<b>PAPER 31: THE DISCOMFORT INDEX PREDICTS THE PHYSIOLOGICAL STRAIN ASSOCIATED WITH INDOOR SPORTS HEAT STRESS</b>	
R.D. Hansen .....	167

<b>PAPER 32: OCCUPATIONAL HEAT ILLNESS: AN INTERVENTIONAL STUDY</b>	
R.J. Brake and G.P. Bates.....	170
<b>POSTER 1: NECK MUSCLE FATIGUE ISSUES RELATED TO NIGHT VISION GOGGLE USE</b>	
C. Brady and V. Demczuk.....	173
<b>POSTER 2: HEAT STRAIN DURING COMBAT FITNESS ASSESSMENT OF SOLDIERS IN NORTHERN AUSTRALIA.</b>	
J.D. Cotter, W.S. Roberts, D. Amos, W.M. Lau and S.K. Prigg .....	176
<b>POSTER 3: THE EFFECTIVENESS OF AN ICE VEST OR INTRAVENOUS ADMINISTRATION OF FLUID ON RECOVERY FROM HIGH HEAT STRAIN.</b>	
J.D. Cotter, G.G. Sleivert and W.S. Roberts.....	179
<b>POSTER 4: EFFECT OF ENVIRONMENTAL TEMPERATURE ON THE ANAEROBIC CAPACITY OF HEAT ACCLIMATISED ATHLETES</b>	
J.P. Finn, J.F. Marsden, R.J. Wood and A.L. Travar .....	183
<b>POSTER 5: COMPARISON OF TWO SYSTEMS OF WATER DELIVERY FOR USE ON MILITARY OPERATIONS</b>	
C.H. Forbes-Ewan, J.D. Cotter, D. Amos and W.M. Lau .....	186
<b>POSTER 6: USE OF SENSORS TO STUDY THE MICROCLIMATE WITHIN A CLOTHING ENSEMBLE</b>	
P. Forshaw.....	189
<b>POSTER 7: IMPACT OF PERSONAL COOLING SUITS ON AN INFANTRY ATTACK SCENARIO</b>	
W. Hobbs, T. Castles and M. French .....	191
<b>POSTER 8: ORIGIN AND REGULATION OF METABOLIC HEAT</b>	
K.P. Ivanov .....	195
<b>POSTER 9: RESTORATION OF PHYSIOLOGICAL FUNCTIONS IN A COOLED ORGANISM WITHOUT REWARMING THE BODY</b>	
K.P. Ivanov .....	199
<b>POSTER 10: THE EFFECT OF AIR GAP ON THE FABRIC SURFACE APPARENT TEMPERATURE AND ITS THERMAL RESISTANCE</b>	
B. Lee.....	203
<b>POSTER 11: MICROCLIMATE OF THE SM1 TANK IN STATIONARY CONDITION</b>	
L.C. Leong, E. Song and S.B. Kee.....	207
<b>POSTER 12: IMPROVING THE MILITARY'S WET WEATHER GARMENT</b>	
D.J. Robinson and G.T. Egglestone. ....	210
<b>POSTER 13: PREDICTION OF THERMAL STRAIN USING NEURAL NETWORKS</b>	
P.J. Sanders and W.M. Lau.....	213
<b>POSTER 14: THE COMBINED EFFECT OF HEAT AND CARBON MONOXIDE ON THE PERFORMANCE OF THE MOTORSPORT ATHLETE</b>	
S.M. Walker, T.R. Ackland and B. Dawson .....	217



# INVITED LECTURE 4: SWEATING IN EXTREME ENVIRONMENTS: HEAT LOSS, HEAT ADAPTATION, BODY-FLUID DISTRIBUTION AND THERMAL STRAIN.

N.A.S. Taylor.

Department of Biomedical Science, University of Wollongong, NSW, Australia.

## INTRODUCTION

Evaporation is an extremely powerful cooling process. When totally evaporated from the skin surface, sweat can remove body heat at a rate of  $2.43 \text{ kJ}\cdot\text{g}^{-1}$ . Humans therefore control sweat secretion to maintain thermal homeostasis. Since humans are capable of extended sweat rates approximating  $30 \text{ g}\cdot\text{min}^{-1}$ , it is possible to remove heat at rates  $\sim 73 \text{ kJ}\cdot\text{min}^{-1}$ . Assuming a 20% efficiency, such heat loss will support a normothermic total energy use of 1520W. This equates with an external work rate of 304W, eliciting an oxygen consumption  $>3.5 \text{ l}\cdot\text{min}^{-1}$ . However, while man has a great capacity to both work and dissipate metabolically-derived heat, exercise under various environmental extremes may impede heat dissipation. Under such conditions, the cumulative effects of metabolic and environmental thermal loads may represent an uncompensable heat stress, predisposing to hyperthermia.

## THE PHYSIOLOGICAL SIGNIFICANCE OF SWEAT

Evaporative cooling in terrestrial beings is perpetual, occurring from the respiratory tract with every breath, and via water-permeable membranes. Resting normothermic man, within a cool-temperate environment, evaporates  $30\text{-}33 \text{ g}\cdot\text{h}^{-1}$  from each surface, with the corresponding cooling effect accounting for the dissipation of about 25% of the resting metabolic heat production. This occurs without our awareness: insensible evaporation. When faced with an external heat load, thermosensitive cells within the skin, and eventually those within deeper tissues, communicate this altered thermal status to the hypothalamus for interpretation. Hypothalamic integration of thermal messages results in the generation of a 'load error' message, to which a proportional sympathetic response is elicited: eccrine sweating.

Apart from man, a number of species possess the ability to sweat actively in response to thermal stress. In man, considerable inter-individual differences are apparent for sweat gland densities and secretion rates [1, 2]. Indeed, men generally sweat more than women [3], and even racial differences exist [4]. While euhydrated people can sustain insensible losses indefinitely, dehydration will occur during active sweating, if water replacement is not elevated proportionately. For instance, daily sweat rates can increase from 300-400 ml, to 10-15 litres during prolonged heat and exercise exposure. Extended-duration sweating of  $1.5\text{-}1.8 \text{ l}\cdot\text{h}^{-1}$  ( $30 \text{ g}\cdot\text{min}^{-1}$ ) is commonly observed and, under severe heat stress, glands can secrete up to  $3\text{-}4 \text{ l}\cdot\text{h}^{-1}$ .

It has been estimated that we have between 1.6-4.0 million sweat glands [5], with considerable variability in gland density between regions. Each gland consists of a secretory coil, connected to the skin surface. As sweat moves through the duct, sodium, chloride and bicarbonate ions are reabsorbed [6]. Sweating typically starts by recruiting groups of glands innervated by the same sympathetic nerve. At rest, sweating generally starts at the extremities, moving towards the head as thermal strain increases [7]. However, we have shown that, with the exception of an earlier lower torso sweat onset, between-site sweat recruitment is generally uniform during upright exercise [8]. During sustained sweating, sweat is secreted across the body surface in a cyclic pattern, reflecting the rhythm of sympathetic activity. As thermal strain rises, the frequency of glandular stimulation is elevated. During the phase conversion from liquid to gas, the water

molecules do not themselves change temperature, but simply absorb thermal energy to drive evaporation. With the evaporation of 1 g of sweat, 2.43 kJ of heat is removed.

### **FACTORS WHICH AFFECT SWEAT EVAPORATION**

The evaporation of sweat is influenced by the water vapour pressure of the surrounding air, but is mainly determined by that of the microclimate above the skin, with water passing down the vapour pressure gradient. Thus, any factor that affects this gradient will impact upon evaporative cooling. Six such factors will be covered within this presentation.

Immediately above the skin is a very thin layer of air, which behaves as though it was trapped in permanent contact with the skin: the boundary layer. For evaporation to occur, the water vapour pressure of the boundary layer must be less than that of the skin surface. Since both the size and composition of the boundary layer are an inverse function of air velocity (relative or absolute), both environmental water vapour pressure (reflected within relative humidity) and wind speed can modify evaporative cooling. The single greatest impact upon the boundary layer is brought about by the use of clothing. While some clothing ensembles allow air to pass through the fabric and apertures, less permeable garments trap air. In such ensembles, locomotion largely determines garment ventilation [9], and trapped air water vapour pressure.

The above factors represent physical changes. Evaporative cooling also depends upon physiological variations. Continuous sweating, at high flows, leads to sweat accumulation, and eventually sweat suppression (hidromeiosis: [10]). This is generally attributed to water-induced swelling of subcutaneous tissues, leading to pore blockage. Hydration status affects heat loss by reducing the core temperature threshold for sweating onset, the sensitivity of the sweat response to such changes, and local sweat rates [11]. On the other hand, adaptation to both endurance training and heat have been shown to increase sweat rates [12].

### **SWEATING AND BODY-FLUID COMPARTMENTS**

The human body is about 60% water (500-600 ml.kg<sup>-1</sup>: female-male), which, while stored within various compartments, is free to move between these sites. Water, the primary substrate for sweat, is drawn from this reservoir. The total volume of water stored is a function of hydration state [11], body composition [13], and endurance exercise adaptation [14]. For instance, a low adiposity is associated with the storage of a larger water volume relative to body mass, due to the higher water content of lean tissue relative to fat [13]. During exercise, we have shown that fluid losses are drawn almost equally from the intracellular and extracellular compartments [15]. The plasma volume forms a sub-division of the extracellular volume, and is generally defended in cool and temperate, but not within hot environments [15]. If not replaced, fluid losses result in progressive dehydration, impaired physiological function and dysthermia.

### **HEAT ADAPTATION**

It was believed that heat adaptation (acclimation) might influence the regional distribution of sweating, favouring greater limb sweating. Past experiments from our laboratory have demonstrated that, while adaptation enhances sweating by elevating sweat rate and lowering its onset threshold [12, 16], it was not associated with a sweat redistribution [16]. For any site, the post-adaptation sweat responses appeared more closely related to differences in sweat gland density, than to altered control of the sweat glands.

Heat adaptation is known to affect body-fluid volumes. Typically, post-adaptation elevations in body fluid, including the plasma compartment, are observed [17]. However, until recently, it was accepted that the plasma lost during combined heat and exercise stress would be diminished following heat adaptation. We now know this to be somewhat

imprecise. Instead, the post-adaptation plasma volume increase is also associated with a greater post-adaptation plasma loss [17]. We have observed that plasma losses, during heat and exercise stress, increase from 16% prior, to 22% following, extended heat adaptation [17]. Thus, the plasma volume was not preferentially defended. Instead, the heightened sweat losses and elevated resting plasma volume, resulted in an elevated plasma contribution to fluid losses following heat adaptation.

### CONCLUSION

We have seen that, while the evaporation of sweat serves a very powerful cooling function, it may be impeded by changes in the boundary layer air and hydration state. On the other hand, endurance training and heat adaptation enhance sweat secretion. However, such changes need not necessarily be associated with greater evaporative cooling, which remains dependent upon the water vapour pressure gradient between the skin and the boundary layer air.

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