Image Cover Sheet

CLASSIFICATION UNCLASSIFIED	**SYSTEM NUMBER** 511492

TITLE

Considerations for the Measurement and Analysis of Heat Debt for Cold Exposure

System Number:

Patron Number:

Requester:

Notes:

DSIS Use only:

Deliver to:

Journal of the Human-Environment System
Vol.2; No.1: 9-18, 1999

Considerations for the Measurement and Analysis of Heat Debt for Cold Exposure

Peter Tikuisis

Defence and Civil Institute of Environmental Medicine
Human Protection and Performance, Canada

(received 8 Oct. 1998; accepted 16 Jan. 1999)

Abstract

The calculation of heat debt through indirect calorimetry requires an accurate assessment of the various components of heat production and heat loss. This paper presents methods of analysis and interpretation of data based on a review of recent advances. Topics include the assessment of body characteristics (surface area, body fat, specific heat, and deep body and skin temperatures), metabolic heat production and shivering metabolism, sensible (conductive, convective, radiative) and insensible (sweating) heat losses, respiratory heat losses, and concludes with a critical examination of mean body temperature. Where measurements of certain variables are unavailable, methods of prediction are suggested.

Key Words: cold stress, heat storage, calculation, prediction, modelling

Introduction

Despite the many technological advances to protect the individual against planned or accidental cold exposure, the risk of serious injury or lethal hypothermia has not been eradicated. Several laboratories continue to be engaged in research to fully understand the human response to cold exposure to improve the protection and performance of the individual. To meet this objective, accuracy is paramount in the presentation of results. Accuracy and the subsequent interpretation of data are facilitated through standardization, yet various methods of analysis are applied. The purpose of this paper is to present methods of analysis and interpretation of data based on a review of recent advances. This is not intended to be an exhaustive review, but rather one that should provide the reader with sufficient information to proceed with a complete analysis of heat debt.

While the present focus is on cold exposure, many of the methods discussed are applicable to thermal strain in general. We begin with the basic heat balance equation which defines the variables of interest (IUPS 1987):

$$S = MR - (C) - (R) - (K) - (E) \qquad (1)$$

where S is the rate of heat storage usually expressed in watts and normalized by body surface area ($W \bullet m^{-2}$ used herein; -ve values imply heat debt), MR is the rate of metabolic heat production, and C, R, K, and E are the convective, radiative, conductive, and evaporative rates of heat loss (the parenthesis indicates that each variable can have a negative value in which case heat is transferred to the body). For convenience with regard to measurement and analysis, the terms of Eq. 1 are rearranged so that:

$$S = MR - (H) - (E_v) - (Q_r) \qquad (2)$$

where H combines C, R, and K, is confined to the surface and is also referred to as the sensible heat loss, E_v is the evaporative rate of heat transfer also confined to the surface of the body whether bare or clothed and is labelled as the insensible heat loss, and Q_r is the respiratory rate of heat transfer which involves evaporative and convective components. Each variable will be examined separately in terms of its measurement and prediction. Finally, the relationship between heat debt and the change in mean body temperature as determined solely by core and skin temperatures will be critically examined.

Body Characteristics

Body surface area and body fatness are two variables that are often applied to normalize data or to interpret the subject response to cold. The most cited estimation of body surface area (SA in m^2) is from DuBois and DuBois (1916) based on a sample of only nine subjects. While their "height-weight" formula is consistent with the dimensionality of the body, more recent analyses have generated better estimates of the parameter values. In particular, the following was regressed by Gehan and George (1970) from a sample of 401 direct measurements of body surface area:

$$SA = 0.1644 \cdot WT^{0.51456} \cdot HT^{0.42246} \qquad (3)$$

where WT and HT are the mass (kg) and height (m) of the individual (gender invariant).

Body fatness provides natural insulation and is associated with an individual's ability to defend against heat loss. The most direct measure of body fatness is through underwater weighing which yields body density, ρ. From density, body fatness can be calculated according to:

$$\%BF = 100 \cdot \left(\frac{4.570}{\rho} - 4.142 \right) \qquad (4)$$

derived by Brozek et al. (1963) as the most appropriate estimation for the general population where ρ is in gm•ml^{-1}. In the absence of body density, fatness can be estimated from the subcutaneous fat measured at various sites on the body, as demonstrated by Durnin and Wormersley (1974) who regressed a relatively simple expression involving 2 parameters. A more recent and complex version with greater accuracy is the "Applied Behnke-Wilmore" procedure (Plyley et al. 1986):

$$\%BF = \frac{\sum_{i=1}^{5} SKF_i}{3 \cdot K_{SKF} \cdot \sqrt{0.1 \cdot WT / HT}} \qquad (5)$$

where SKF is the skinfold thickness in mm, the 5 sites are the triceps, subscapular, suprailiac, abdomen, and front thigh regions, and the fitting parameter K_{SKF} is equal to 0.658, 0.634, and 0.635 for females, and 0.724, 0.716, and 0.634 for males of < 30, 30 - 39, and > 39 yr of age, respectively.

Other methods of body fat determination include air displacement, bioelectrical impedance, dual energy X-ray absorptiometry, and near infrared interactance. Once body fat mass is known, the specific heat of the body can be approximated from the following formula where the coefficients represent the specific heats (in kJ•kg$^{-1}\cdot$°C^{-1}) of fat and non-fat tissues of the body (Minard 1970; Webb 1993):

$$c_b = 1.88 \cdot WT_{fat} + 3.72 \cdot WT_{non-fat} \qquad (6)$$

The specific heat of fat cited above is considerably lower than the values commonly used [eg., 2.09 - 2.51 kJ•kg$^{-1}\cdot$°C^{-1} (Werner and Buse 1988)]; however, it represents 'pure' fat while the non-fat value is characteristic of muscle and organ tissue. As will be seen later, specific heat is required to calculate the change in mean body temperature from heat debt; yet, differences in the value of c_b assumed do not greatly affect the discrepancy between the calculated and measured heat debt (Burton and Edholm 1955).

Core or deep body temperature (T_c) has been represented by various locations including esophageal, tympanic, and rectal. The choice is often based on which location adequately reflects the physiological response to the cold stress and on practical considerations such as subject tolerance (Ogawa 1997). Whatever method is chosen, investigators should be aware of the effects that cold stress places on the measurements of these sites (Livingstone et al. 1983).

Mean skin temperature ($\overline{T}_{sk}$) is usually determined by weighting the measured skin temperatures at specific sites on the body. Olesen (1984) confirmed that one of the most accurate estimates of $\overline{T}_{sk}$ is based on the following 12-point Hardy-DuBois formula (1938):

$$\overline{T}_{sk} = \sum_{i=1}^{12} a_i \cdot T_{sk_i} \tag{7}$$

where a = 0.07 (forehead), 0.0875 (scapula, chest, abdomen, lower back), 0.14 (lower upper arm), 0.05 (hand), 0.095 (front thigh, back thigh), 0.065 (shin, calf), and 0.07 (foot). Reducing the number of skin temperature sites to 7 (also considered by Hardy and DuBois) can more than double the standard error of estimation.

Heat Production (*MR*)

The accepted method of measurement of the rate of metabolic heat production is through the rate of oxygen consumption, $\dot{V}O_2$ (in $l_{STPD} \cdot min^{-1}$). If the rate of carbon dioxide production, $\dot{V}CO_2$, is also known, then the metabolic rate (in $W \bullet m^{-2}$) can be computed from the following relationship extracted from Peronnet and Massicotte (1991):

$$MR = (281.65 + 80.65 \cdot RER) \cdot \frac{\dot{V}_{O_2}}{SA} \tag{8}$$

where *RER* is the respiratory exchange ratio ($\dot{V}CO_2/\dot{V}O_2$). If $\dot{V}CO_2$ is not known, then the above equation can still be used by assuming a value for *RER* without incurring too great an error. This is because of the low sensitivity of *MR* to *RER*. For example, a change in *RER* from a reference value of 0.85 by ± 0.15 (representing the maximum physiological range for non-protein oxidation) would lead to an error of less than 3.6% in *MR*.

If the metabolic rate is not measured during cold exposure, its value can be predicted if the deep body and mean skin temperatures are known. A recent study has confirmed the findings of Benzinger (1969) that the shivering stimulus from skin temperature increases to a maximum near 20°C and then decreases again. This study (Tikuisis and Giesbrecht 1999) examined the data of several males immersed in 8°C water for up to 1 h who then rewarmed *via* shivering under dry blanketed conditions. The lowest deep body temperature attained was 33.25°C. A regression of all the subjects' metabolic responses (in $W \bullet m^{-2}$) yielded the following formula:

$$MR_{shiv} = \frac{155.5 \cdot (37 - T_c) + 47.0 \cdot (33 - \overline{T}_{sk}) - 1.57 \cdot (33 - \overline{T}_{sk})^2}{\sqrt{\%BF}} \tag{9}$$

where 33 and 37 are temperature shivering setpoints. The values in parenthesis are set equal to zero whenever the actual temperature exceeds its setpoint value. Note the attenuating effect of body fatness which was first identified in an earlier study regarding metabolic responses to cold exposure (Tikuisis et al. 1988). Not accounting for differences in body fatness can lead to large errors (eg., if actual *BF* is half or double the assumed value, then MR_{shiv} might be under or overestimated, respectively, by 41%).

Sensible Heat Loss (*H*)

The rates of convective and radiative heat losses are usually combined (conductive heat exchange is discussed further below) and measured through calorimetry either directly (*via* a heat exchanger) or indirectly [using heat flux transducers (HFT)]. The latter involves the same sites used to determine $\bar{T}_{sk}$ and the same weighting coefficients apply (see Eq. 7). However, care must be exercised when interpreting the measured heat flux. Since the HFT has a physical dimension, it imposes a thermal resistance (*RT* in $^{\circ}C\bullet m^2\cdot W^{-1}$ derived from its thickness divided by thermal conductivity) which causes an underestimation in the measured heat flux (Ducharme et al. 1990). The appropriate correction is given by (Strong et al. 1985):

$$H_{corr} = \frac{H_{meas}}{1 - \frac{RT\cdot H_{meas}}{(T_c - T_a)}} \qquad (10)$$

where T_c is the core temperature most closely associated with the site of measurement. Ducharme et al. (1990) demonstrated that the above correction can range from 3 - 13% during vasoconstriction and from 29 - 35% during vasodilation.

If the heat flux is not measured, then $C+R$ can be estimated according to (Parsons 1993):

$$C + R = \frac{T_{sk} - T_o}{I_T + (f_{cl}\cdot h)^{-1}} \qquad (11)$$

T_o is the "operative" temperature given by:

$$T_o = \frac{h_c\cdot T_a + h_r\cdot T_r}{h_c + h_r} \qquad (12)$$

where T_r is the mean radiant temperature [see Parsons (1993) for details on its measurement]. I_T is the clothing insulation (in units of $m^2\cdot{}^{\circ}C\bullet W^{-1}$) which is often expressed in terms of "clo" (= 0.155 $m^2\cdot{}^{\circ}C\bullet W^{-1}$ or $I_{clo} = I_T/0.155$). f_{cl} is the clothing area factor (ratio of clothed to nude surface areas) approximated by:

$$f_{cl} = 1 + \kappa\cdot I_T \qquad (13)$$

where κ varies between 1 and 2.3 (Aoyagi et al. 1997). Higher values are associated with increased amounts of clothing [the value of 2.0 is commonly used for indoor clothing (McCullough and Jones 1984) and for general assessment (ISO 9920)]. h is the combined convective and radiant heat transfer coefficients (i.e., $h = h_c + h_r$; in $W\bullet m^{-2}\cdot{}^{\circ}C^{-1}$). The convective component can be approximated by (Nishi 1981):

$$h_c = a\cdot v^b{}_{movement} + c\cdot v^d{}_{wind} \qquad (14)$$

where v is velocity in $m\bullet s^{-1}$, and $\{a, b, c, d\}$ are fitted parameters with values of {0, 0, 11.6, 0.5} for sitting only, {6.5, 0.39, 0, 0} for treadmill walking/running with no wind, and {8.6, 0.53, 2.0, 0.86} for free walking/running with wind. The radiative heat transfer coefficient can be approximated by (Nishi 1981):

$$h_r = 4\varepsilon\sigma\cdot\frac{A_r}{SA}\cdot\left(273.15 + \frac{T_{surface} + T_r}{2}\right)^3 \qquad (15)$$

where ε is the emissivity of the surface (between 0.95 and 1), σ is the Stefan-Boltzmann constant ($5.67\bullet10^{-8}$ $W\bullet m^{-2}\cdot{}^{\circ}C^{-4}$), and A_r is the radiating surface area.

In water, the heat transfer coefficient is solely convective and can be estimated by (Boutelier et al. 1977):

$$h_c = a + b\cdot v^c \qquad (16)$$

where v is the flow velocity in m•s^{-1} and $\{a, b, c\}$ are fitted parameters with values of {41.4, 415, 1.0} for no shivering and $v < 0.06$ m•s^{-1}, {0, 273, 0.5} for no shivering and $v \geq 0.06$ m•s^{-1}, {53.1, 590, 1.0} with shivering and $v < 0.11$ m•s^{-1}, and {0, 497, 0.65} with shivering and $v \geq 0.11$ m•s^{-1}.

The conductive rate of heat loss in the heat balance equation is applicable if the individual has direct physical contact with a conductive surface, otherwise the above expressions suffice if the individual is surrounded by air and/or water. The reader is referred to Sekins and Emery (1982) for guidance on the calculation of conductive heat loss through direct contact with a solid. Heat will conduct through clothing, but this value will be inherently captured by measures of heat transfer at the clothing surface (*via* HFT) or by direct calorimetry. If the conductive rate of heat loss through clothing is required, it can be calculated from (Nishi 1981):

$$K = \frac{\kappa}{I_T} \cdot \left(T_{sk} - T_{cl}\right) \qquad (17)$$

where T_{cl} is the clothing surface temperature. The insulation value will decrease considerably if the clothing is wet; in essence, the thermal conductivity of "trapped" air becomes displaced by the much higher thermal conductivity of "still" water.

Insensible Heat Loss (E_s)

Sweating is usually not a factor during cold exposure, however, an individual may be wet for other reasons and thus is subject to evaporative heat loss. If a direct measure of the rate of evaporation [eg., capsulation, gradient method, 3-point sensor (Kakitsuba and Katsuura 1992)] is not available, then its value can be estimated. For bare skin (Nishi 1981):

$$E_v = f_w \cdot 16.5 \cdot h_c \cdot (P_{sk} - P_a) \qquad (18)$$

where f_w is the fraction of wetted skin, 16.5 is the Lewis relation in °C•kPa^{-1}, and P_{sk} (= $P_{sat(Tsk)}$) and P_a (= $RH \bullet P_{sat(Ta)}$ where RH is the fractional relative humidity and T_a is the ambient temperature) are the vapour pressure at the skin surface and the ambient vapour pressure in kPa, respectively. Antoine's equation (Parsons 1993) provides an excellent approximation of the saturation vapour pressure as a function of temperature, T (in °C).

$$P_{sat(T)} = \exp\left(16.6536 - \frac{4030.183}{T + 235}\right) \qquad (19)$$

If the skin is wet and clothed, then the evaporative heat loss can be estimated (Oohori et al. 1984) by multiplying Eq. 18 by $f_{cl} \cdot F_{pcl}$ where F_{pcl} is the permeation efficiency factor:

$$F_{pcl} = (1 + 2.2 \cdot f_{cl} \cdot h_c \cdot I_T)^{-1} \qquad (20)$$

Respiratory Heat Loss (Q_r)

Respiratory heat losses comprise convective and evaporative components governed by the subject's rate of ventilation ($\dot{V}$ in $\mathrm{l_{STPD}} \cdot \mathrm{h}^{-1}$; Cain et al. 1990):

$$Q_r = \left(\frac{1}{SA}\right) \cdot \left[\rho \cdot \dot{V} \cdot (c_a + \gamma_a \cdot c_v) \cdot (T_e - T_a) + \rho \cdot \dot{V} \cdot \lambda \cdot (\gamma_e - \gamma_a)\right] \qquad (21)$$

where ρ is the density of air (0.001293 kg•l$^{-1}_{\mathrm{STPD}}$), λ is the latent heat of vapourization [= 673 W•h•kg^{-1} (2423 kJ•kg^{-1}) at 33°C], c is the specific heat [subscripts a and v refer to the air (0.28 W•h•kg^{-1} · °C^{-1} (1.01 kJ•kg^{-1})) and vapour, respectively], the subscript e refers to the expired air, and γ is the humidity ratio [mass of water vapour to the mass of air in the inspired or expired mixture = $0.622 \cdot P/(101 - P)$ where P is the relevant vapour pressure in kPa (Reynolds and Perkins 1977)]. The expired air temperature can be approximated by (McCutchan and Taylor 1951):

$$T_e = 32.6 + 0.066 \cdot T_a + 32 \cdot \gamma_a \tag{22}$$

If the individual's ventilation rate is not known, then Q_r can be estimated from the metabolic rate as follows (Fanger 1970):

$$Q_r = 0.0014 \cdot MR \cdot (34 - T_a) + 0.0173 \cdot MR \cdot (5.87 - P_a) \tag{23}$$

Mean Body Temperatre (T_b)

Changes in mean body temperature (T_b) are often used to determine the heat debt of the body, especially in the absence of a direct or indirect calometric determination. Many investigators continue to apply the 2-node approach proposed by Burton (1935):

$$T_b = x \cdot T_c + (1 - x) \cdot \overline{T}_{sk} \tag{24}$$

The value of the adjustment parameter, x, is intended to approximate the thermal mass of the body whose temperature corresponds to the core while the remaining portion represents the "shell" of the body. These proportions have subsequently been found to vary depending on the thermal stress applied, ranging from $x = 0.6$ to 0.9 for cold to warm exposures. The difficulty with the 2-node approach is its application to individuals that experience a transition in thermal stress, as pointed out by Livingstone (1968). At what point after the transition x is changed from its initial value becomes arbitrary. Livingstone concluded that the adjustment parameter must vary continuously to reflect the non-steady state change in true mean body temperature.

To illustrate this point, data were adopted from a cold air exposure (2 h at 10°C) involving 5 males at rest wearing shorts only (Tikuisis et al. 1991). Mean values of core and mean-weighted skin temperatures are plotted in Fig. 1 (a) and (b). Assuming that the subjects were thermoneutral at the start of the exposure, the adjustment parameter can be assigned an initial value of 0.79 (Bittel 1987). Using Eq. 24, the change in T_b can then be expressed as:

$$\Delta T_b = 0.79 \cdot T_{c,0} + 0.21 \cdot \overline{T}_{sk,0} - x \cdot T_c - (1 - x) \cdot \overline{T}_{sk} \tag{25}$$

where the subscript "0" denotes the initial thermoneutral value. From measurements of heat production and heat loss recorded in the study, the heat debt can be calculated; its rate of change and cumulative change are shown in Fig. 1 (c) and (d), respectively.

The "true" change in mean body temperature is given by the heat debt divided by the body's specific heat, i.e.:

$$\Delta T_b = \frac{1}{c_b} \int S \cdot dt \tag{26}$$

By direct comparison (i.e., equating Eqs. 25 and 26), the changing value of x for conformity can be deduced and is plotted in Fig. 1 (e). The resultant initial transient rise in x places greater weight on core than mean skin temperature. This adjustment compensates for the rapid initial decrease in $\overline{T}_{sk}$ which overestimates the decrease in the temperature of deeper subcutaneous tissue. Hence, the thermal mass of the "shell" is temporarily reduced as a consequence of mathematically balancing the heat distribution in the body. Once the value of x decreases, it continues beyond the value of 0.67 often assumed for cold stress (Bittel 1987) and in this case without any indication of where it would terminate once a steady state condition is reached.

An alternative approach to evaluating mean body temperature is to disregard changes in the adjustment parameter and to introduce an intermediate region of the body, denoted as "mid", whose temperature would fall

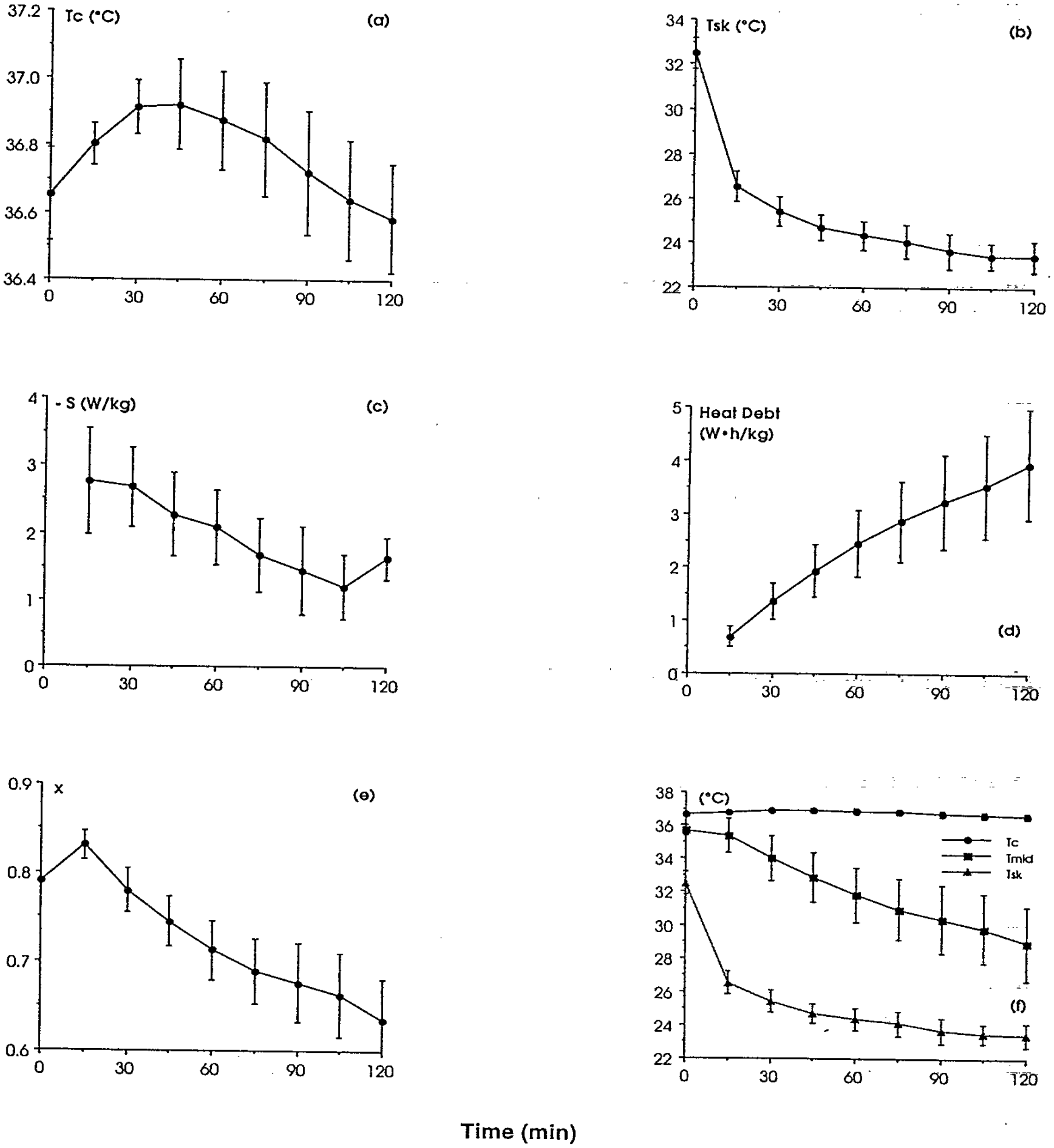

Fig. 1. Plots of mean ± SD of (a) core temperature, (b) mean-weighted skin temperature, (c) rate of heat debt, and (d) heat debt of 5 males exposed to 10°C air for 2 h in a supine position and wearing shorts only. (e) shows the value of the adjustment parameter in the 2-node model of T_b (Eq. 24) for consistency with the measured heat debt, and (f) shows the temperature of the intermediate tissue of the 3-node model of T_b (Eq. 27) without any parameter adjustments.

between the core and skin, eg.:

$$T_b = x_c \cdot T_c + x_{mid} \cdot T_{mid} + (1 - x_c - x_{mid}) \cdot \overline{T}_{sk} \tag{27}$$

As a hypothetical example, consider assigning a weight to the surface region based on the individual's body fatness, as proposed by Kakitsuba and Mekjavic (1987) (i.e., $1 - x_c - x_{mid}$ = %BF/100), and assume equal weights for the core and mid regions (i.e., $x_c = x_{mid}$). By repeating the heat balance calculations without any further adjustments in the values of x, the values of T_{mid} can be deduced and are shown in Fig. 1 (f) for the data described above. As expected, T_{mid} falls between the mean skin and core temperatures. Although overly simple, this example helps illustrate the considerable and continuous cooling of the portion of the body sandwiched between the core and skin as the skin approaches its steady state temperature while heat debt continues to rise.

It is evident that more realistic temperature distributions (with smaller discontinuities) can be attained by increasing the number of regions as demonstrated by finite element models of whole body thermoregulation (eg., Werner and Buse 1988). While multi-compartmental models may be too unwieldy for some heat balance analyses, a 2-node approach with an adjustable parameter is unrealistic for determining the mean body temperature under non-steady state conditions. Changes in T_b are most accurately determined through Eq. 26 where the rate of heat storage is measured *via* direct/indirect calorimetry.

Concluding Remark

This brief overview was intended to promote a standard approach among investigators by presenting recent advances on the methodology of the measurement and analysis of heat debt. Details on specific items are left to the reader to pursue through the citations. An important consideration that remains to be explored is the sensitivity of the various components of the heat balance equation to the overall assessment of heat debt. Such a sensitivity analysis would assist investigators in their allocation of effort and resources to measure heat debt, and in the interpretation of their results.

Acknowledgement

The author gratefully appreciates the expert opinion and advice given by Dr. Randall Osczevski during the preparation of this paper.

References

1. Aoyagi, Y., McLellan, T.M. and Shephard, R.J. (1997) 'Interactions of physical training and heat acclimation' Sports Med. 23(3), 173-210.
2. Benzinger, T.H. (1969) 'Heat regulation: homeostasis of central temperature in man' Physiol. Rev., 49(4), 671-759.
3. Bittel, J.H.M. (1987) 'Heat debt as an index for cold adaptation in men' J. Appl. Physiol. 62, 1627-1634.
4. Boutelier, C., Bouges, L. and Timbal, J. (1977) 'Experimental study of convective heat transfer coefficient for the human body in water' J. Appl. Physiol. 42, 93-100.
5. Brozek, K., Grande, F., Anderson, J.T. and Keys, A. (1963) 'Densitometric analysis of body composition: revision of some quantitative assumptions' Ann. NY Acad. Sci., 110, 113-140.
6. Burton, A.C. (1935) 'The average temperature of the tissues of the body' J. Nutrition 9, 261-268.
7. Burton, A.C. and Edholm, O.G. (1955) 'Man In A Cold Environment' Edward Arnold, London, pp. 41-42.
8. Cain, J.B., Livingstone, S.D., Nolan, R.W. and Keefe, A.A. (1990) 'Respiratory heat loss during work at various ambient temperatures' Resp. Physiol. 79, 145-150.

9. DuBois, D. and DuBois, E.F. (1916) 'Clinical calorimetry. A formula to estimate the approximate surface area if height and weight be known' Arch. Intern. Med., 17, 863-871.
10. Ducharme, M.B., Frim, J. and Tikuisis, P. (1990) 'Errors in heat flux measurements due to the thermal resistance of heat flux disks' J. Appl. Physiol. 69(2), 776-784.
11. Durnin, J.V.G.A. and Womersley, J. (1974) 'Body fat assessed from total 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.
12. Fanger, P.O. (1970) 'Thermal Comfort' McGraw-Hill, NY, pp. 28-30.
13. Gehan, E.A. and George, S.L. (1970) 'Estimation of human body surface area from height and weight' Can. Chemotherapy Rep. Part 1 54(4), 225-235.
14. Hardy, J.D. and DuBois, E.F. (1938) 'The technic of measuring radiation and convection' J. Nutr. 15, 461-475.
15. ISO 9920 (1992) 'Estimation of the thermal characteristics of a clothing ensemble' International Standards Organization, Geneva, Switzerland.
16. IUPS Thermal Commission (1987) 'Glossary of terms for thermal physiology' Pflugers Arch., 410, 567-587.
17. Kakitsuba, N. and Mekjavic, I.B. (1987) 'Determining the rate of body heat storage by incorporating body composition' Aviat. Space Environ. Med., 58, 301-307.
18. Kakitsuba, N. and Katsuura, T. (1992) 'Development of a new device to measure local heat exchange by evaporation and convection' Aviat. Space Environ. Med., 63, 538-542.
19. Livingstone, S.D. (1968) 'Calculation of mean body temperature' Can. J. Physiol. Pharmacol. 46, 15-17.
20. Livingstone, S.D., Grayson, J., Frim, J., Allen, C.L. and Limmer, R.E. (1983) 'Effect of cold exposure on various sites of core temperature measurements' J. Appl. Physiol., 54(4), 1025-1031.
21. McCullough, E.A. and Jones, B.W. (1984) 'A comprehensive data base for estimating clothing insulation' ASHRAE 411-RP and Institute for Environmental Research Technical Report 84-01, Kansas State University, Manhattan, KA.
22. McCutchan, J.W. and Taylor, C.L. (1951) 'Respiratory heat exchange with varying temperatures and humidity of inspired air' J. Appl. Physiol., 4, 121-135.
23. Minard, D. (1970) 'Body heat content' In: Hardy, J.D., Gagge, A.P. and Stolwijk, J.A.J. (eds) Physiological and Behavioral Temperature Regulation. Charles C. Thomas, Springfield, IL, pp. 345-357.
24. Nishi, Y. (1981) 'Heat exchange between human body and environment' In: Nakayama, T. (ed) Thermophysiology, Rikogakusha, Tokyo, pp. 33-72.
25. Ogawa, T. (1997) 'Where should core temperature be measured in human experiments?' J. Human-Environ. Sys., 1(1), 47-55.
26. Olesen, B.W. (1984) 'How many sites are necessary to estimate a mean skin temperature?' In: Hales, J.R.S. (ed) Thermal Physiology, Raven Press, NY, pp. 33-38.
27. Oohori, T., Berglund, L.G. and Gagge, A.P. (1984) 'Comparison of current two-parameter indices of vapour permeation of clothing - as factors governing thermal equilibrium and human comfort' ASHRAE Trans. 90(Pt 2A), 85-101.
28. Parsons, K.C. (1993) 'Human Thermal Environments' Taylor & Francis, UK. pp. 12 and 111.
29. Peronnet, F. and Massicotte, D. (1991) 'Table of nonprotein respiratory quotient: an update' Can. J. Spt. Sci. 16, 23-29.
30. Plyley, M.J., Shephard, R.J. and Forsyth, R.D. (1986) 'Development of protocols for accurate measurement of body composition' Contract OISE 97711-2-6886 Report to Defence and Civil Institute of Environmental Medicine, Toronto, Canada.
31. Reynolds, W.C. and Perkins, H.C. (1977)

'Engineering Thermodynamics' McGraw-Hill, NY. pp. 393-395.
32. Sekins, K.M. and Emery, A.F. (1982) 'Thermal science for physical medicine' In: Lehman, J.F. (ed) Therapeutic Heat and Cold. Williams & Wilkins, Baltimore, MD, pp. 70-132.
33. Strong, L.H., Gee, G.K. and Goldman, R.F. (1985) 'Metabolic and vasomotor insulative responses occurring on immersion in cold water' J. Appl. Physiol., 29(5), 964-977.
34. Tikuisis, P., Gonzalez, R.R., Oster, R.A. and Pandolf, K.B. (1988) 'Role of body fat in the prediction of the metabolic response for immersion in cold water' Undersea Biomed. Res. 15(2), 123-134.
35. Tikuisis, P., McCracken, D.H. and Radomski, M.W. (1991) 'Heat debt during cold air exposure before and after cold water immersions' J. Appl. Physiol. 71(1), 60-68.
36. Tikuisis, P. and Giesbrecht, G.G. (1999) 'Prediction of shivering heat production from core and mean skin temperatures' Eur. J. Appl. Physiol. 79(3), 221-229.
37. Webb, P. (1993) 'Heat storage and body temperature during cooling and rewarming' Eur. J. Appl. Physiol. 66, 18-24.
38. Werner, J. and Buse, M. (1988) 'Temperature profiles with respect to inhomogeneity and geometry of the human body' J. Appl. Physiol. 65(3), 1110-1118.

#511492