TITLE

PREDICTION OF SHIVERING HEAT PRODUCTION FROM CORE AND MEAN SKIN TEMPERATURES

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ORIGINAL ARTICLE

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Prediction of shivering heat production from core and mean skin temperatures

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Abstract Prediction formulae of shivering metabolism (M_{shiv}) are critical to the development of models of thermoregulation for cold exposure, especially when the extrapolation of survival times is required. Many such formulae, however, have been calibrated with data that are limited in their range of core temperatures (T_c), seldom involving values of less than 36°C. Certain recent studies of cold-water immersion have reported T_c as low as 33.25°C. These data comprise measurements of T_c (esophageal) and mean skin temperature ($\bar{T}_s$), and metabolism from 14 males [mean (SD); age = 28 (5) years; height = 1.78 (0.06) m; body mass = 77.7 (6.9) kg; body fat (BF) = 18.4 (4.5)%] during immersion in water as cold as 8°C for up to 1 h and subsequent self-rewarming via shivering under dry blanketed conditions. The data contain 3343 observations with mean (SD) T_c and $\bar{T}_s$ of 35.92 (0.93)°C and 23.4 (8.9)°C, respectively, and have been used to re-examine the prediction of M_{shiv}. Rates of changes of these temperatures were not used in the analysis. The best fit of the formulae, which are essentially algebraic constructs with and without setpoints, are those with a quadratic expression involving $\bar{T}_s$. This is consistent with the findings of Benzinger (1969) who demonstrated that the thermosensitivity of skin is parabolic downwards with temperature peaking near a value of 20°C. Formulae that included a multiplicative interaction term between T_c and $\bar{T}_s$ did not predict as well. The best prediction using 37°C and 33°C as the T_c and T_s setpoints, respectively, was found with BF as an attenuation factor: M_{shiv} ($\mathrm{W \cdot m^{-2}}$) = $[155.5 \cdot (37 - T_c) + 47.0 \cdot (33 - \bar{T}_s) - 1.57 \cdot (33 - \bar{T}_s)^2] / (\%\mathrm{BF})^{0.5}$.

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Introduction

It is generally acknowledged that shivering occurs when body temperatures decrease below their normal comfort values. Since the sites of body temperature measurement usually involve the core and skin, predictions of shivering metabolism (M_{shiv}) are largely based on data from these sites. Yet, the number of combinations and permutations of these temperatures is vast and the various formulae that have emerged (Hardy et al. 1970; Miller and Seagrave 1974; Tikuisis et al. 1988) reflect differences in either the data used or in the interpretation of these data for the derivations. Common to most data sets is the relatively narrow range of reported core temperatures T_c, seldom less than 36°C. Reported skin temperatures $\bar{T}_s$, on the other hand, span a reasonably wide range in most cases. The derivation of the prediction formulae for M_{shiv} are therefore heavily weighted on $\bar{T}_s$ and have not been validated for truly hypothermic individuals (T_c of 35°C or less; Collins 1983). Given that the prediction of M_{shiv} is critical to the prediction of survival time for cold exposure (Tikuisis 1995, 1997), verification of the various formulae over a wider range of T_c is essential.

Giesbrecht et al. (1994, 1997) and Giesbrecht and Bristow (1998) have reported a number of recent studies where the T_c of cold-water-immersed individuals fell as low as 33.25°C. These studies have been primarily concerned with rewarming strategies, and cold-water immersions were used to quickly achieve a hypothermic condition. During the course of the individual's cooling and subsequent rewarming, T_c, $\bar{T}_s$, and metabolic rates were measured continuously. Hence, these data present a unique and ideal opportunity to test the various prediction formulae of M_{shiv} in the early stages of hypothermia.

This study will not address the underlying mechanisms that give rise to the shivering response; instead, it will focus on describing this response through mathematical terms. Most prediction formulae for M_{shiv} are algebraic constructs and the majority of these are constrained through the use of setpoints. In this context, shivering setpoints are temperature thresholds below which the body is assumed to shiver. They have no physical presence and have been introduced empirically in the development of control functions for mathematical models of thermoregulation (Brown and Brengelmann 1970). An actual temperature is compared against its corresponding setpoint value and the difference is then considered as the error term or afferent signal that governs the thermoregulatory response. The simplest prediction model considers only an on/off response (Giesbrecht 1994). Most models predict a proportional response to the afferent signal, which is also adopted in this study.

Setpoints (hereafter understood to pertain to shivering only) have typically been referenced to the temperatures of the central and cutaneous regions of the body. They do not represent the onset firing of thermosensors (Hensel 1981), but simply provide a mathematical starting point for predicting the generation of heat via shivering. Their respective values have ranged from 36.5°C and 32.2°C (Nadel et al. 1970) to 37.5°C and 34.0°C (Miller and Seagrave 1974). The intermediate values of 37°C and 33°C assumed by Stolwijk and Hardy (1977) will herein be referred to as the "standard" set. No attempt will be made to include other afferent signals since the present data are limited to the esophageal and mean-weighted skin temperatures.

Two classes of formulae will be examined. One involves the setpoint temperatures directly as described above, and the other is obtained by expanding the setpoint formula algebraically. The latter is free of constraints (i.e., no restriction on the values of body temperatures used) and simply gives weight to the absolute versus relative temperatures of the body. Another major difference between the two approaches lies in the way the data are applied. We begin by outlining selected general forms of the setpoint formulae.

Methods

Formulae

The simplest setpoint formula is a linear combination of T_c and mean skin temperatures ($\bar{T}_s$), as applied by Miller and Seagrave (1974):

$$M_{\mathrm{shiv}} = P_1 \cdot (T_{c,\mathrm{set}} - T_c) + P_2 \cdot (T_{s,\mathrm{set}} - \bar{T}_s) \tag{1}$$

where M_{shiv} is the metabolic rate due to shivering (excludes the resting metabolism), P is the scaling parameter or weighting coefficient, T is the temperature, and the subscripts c, s, and set refer to the core, skin, and setpoint, respectively. A more complex version adds a quadratic term involving the $\bar{T}_s$ which is strongly suggested by the analysis of Benzinger (1969) and inherently takes into account the non-linear sensitivity of the cutaneous cold receptors as reviewed by Hensel (1981):

$$M_{\mathrm{shiv}} = P_1 \cdot (T_{c,\mathrm{set}} - T_c) + P_2 \cdot (T_{s,\mathrm{set}} - \bar{T}_s) + P_3 \cdot (T_{s,\mathrm{set}} - \bar{T}_s)^2 \tag{2}$$

The next formula for consideration is one involving a multiplicative interaction between the T_c and $\bar{T}_s$. Such an interaction was proposed to describe the hyperbolic relationship observed by Bruck and Wunnenberg (1970) and Cabanac (1970) whereby the shivering intensity increases as T_c and $\bar{T}_s$ decrease. Hayward et al. (1977) adopted this relationship and Nadel et al. (1970) added a second linear term involving the skin only, as follows:

$$M_{\mathrm{shiv}} = P_1 \cdot (T_{c,\mathrm{set}} - T_c) \cdot (T_{s,\mathrm{set}} - \bar{T}_s) + P_2 \cdot (T_{s,\mathrm{set}} - \bar{T}_s) \tag{3}$$

Variants of the above equation have subsequently been applied by other investigators; for example, substitution of the second term by one involving the rate of change of T_c (Wissler 1985). Finally, a mixture of the interaction and quadratic terms is considered as applied by Stolwijk and Hardy (1977) and Tikuisis et al. (1988):

$$M_{\mathrm{shiv}} = P_1 \cdot (T_{c,\mathrm{set}} - T_c) \cdot (T_{s,\mathrm{set}} - \bar{T}_s) + P_2 \cdot (T_{s,\mathrm{set}} - \bar{T}_s)^2 \tag{4}$$

Inherent in the use of the above formulae is that each bracketed term has a zero value whenever the actual body temperature exceeds its setpoint value (Brown and Brengelmann 1970). This constraint necessitates the use of censored data whenever the above formulae are regressed against it. That is, terms involving T_c and $\bar{T}_s$ that exceed their corresponding setpoint values are ignored. However, no such restriction applies when the unconstrained algebraic forms are used. These can be found by simply expanding the above formulae and reassigning parameters, as follows. From the linear combination of T_c and $\bar{T}_s$ (Eq. 1):

$$M_{\mathrm{shiv}} = P'_1 + P'_2 \cdot T_c + P'_3 \cdot \bar{T}_s \tag{5}$$

where the prime designation indicates that the scaling parameters are not necessarily equivalent to the parameters of other formulae. Equation 5 was originally proposed by Strong et al. (1985) and involves an additional parameter compared to the setpoint formula (Eq. 1). Timbal et al. (1976) added the rate of change of $\bar{T}_s$ and body surface area (SA) as a modifying factor to the above equation. Anthropometric variables will be considered later.

The quadratic formula (Eq. 2) becomes:

$$M_{\mathrm{shiv}} = P'_1 + P'_2 \cdot T_c + P'_3 \cdot \bar{T}_s + P'_4 \cdot \bar{T}_s^2 \tag{6}$$

Similarly, the interaction (Eq. 3) and interaction-quadratic (Eq. 4) formulae become Eqs. 7 and 8, respectively:

$$M_{\mathrm{shiv}} = P'_1 + P'_2 \cdot T_c + P'_3 \cdot \bar{T}_s + P'_4 \cdot T_c \cdot \bar{T}_s \tag{7}$$

$$M_{\mathrm{shiv}} = P'_1 + P'_2 \cdot T_c + P'_3 \cdot \bar{T}_s + P'_4 \cdot T_c \cdot \bar{T}_s + P'_5 \cdot \bar{T}_s^2 \ . \tag{8}$$

The present study does not consider the rates of change in body temperatures as a driving force for thermogenesis because of the incompleteness in determining these values. That is, the rate of change of temperature is dependent upon the time interval used, which is both arbitrary and subject to how frequently data are collected. Although data were measured continuously in this study, only 30-s averages were recorded. A fair analysis would require the possibility of examining changes over smaller periods of time, especially with regard to abrupt changes in $\bar{T}_s$.

Data

Experimental data for the present study were taken from three separate studies conducted in the same laboratory on a total of 14 different males (Giesbrecht and Bristow 1998; Giesbrecht et al. 1994, 1997). Each study involved cooling via neck-level immersion in water as cold as 8°C for up to 1 h. These studies were approved by the University of Manitoba Faculty Ethics Committee and supervised by a physician. In addition, each subject gave an informed consent to participate in the experiment. Various methods of rewarming were subsequently applied (eg., body-to-body contact with a normothermic donor, warm-air inhalation, exercise); however, the data used here represent control trials and involve self-rewarming by shivering only (in a dry sleeping bag). Rewarming was terminated when the esophageal temperature (T_c) recovered to a minimum of 35.5°C (usually within 1 h).

Table 1 summarizes the subjects' anthropometric measurements and body cooling results. Body surface area (SA, m^2) was determined from the subject's height (HT, m) and body mass (BM, kg) using the following formula of Gehan and George (1970):

$$SA = 0.1644 \cdot HT^{0.4225} \cdot BM^{0.5146} \tag{9}$$

Body fatness (BF) was determined from the sum of four skinfolds (biceps, triceps, subscapular, and suprailiac sites) using the method of Durnin and Womersley (1974). T_c was measured using a thermocouple probe placed in the esophagus at the level of the heart. $\bar{T}_s$ was measured on the head, chest, back, arms, and legs using surface-attached thermal flux transducers. The $\bar{T}_s$ was based on regional representations according to Layton et al. (1983): 6, 19, 19, 19, and 37%, respectively. The minimum core temperatures ($T_{c,\,min}$) and the corresponding times to these values include the afterdrop upon rewarming. Figure 1 shows the T_c and $\bar{T}_s$ observed in subject 11 who attained the lowest T_c.

Metabolism (*M*) was determined from oxygen consumption ($\dot{V}O_2$ in 1 $O_2 \cdot min^{-1}$) using an open-circuit method (Giesbrecht et al. 1994). The conversion to $W \cdot m^{-2}$ was calculated using the following formula, regressed from the nonprotein oxidation analysis of Peronnet and Massicotte (1991):

$$M = (281.65 + 80.65 \cdot \dot{V}CO_2/\dot{V}O_2) \cdot (\dot{V}O_2/SA) \tag{10}$$

where $\dot{V}CO_2$ is production of CO_2. Each observation per subject (based on 30-s averages) was assigned a case weight determined by the reciprocal of the total number of observations taken for that subject, so that all observations were equally represented. The overall number of observations was 3343 with mean (SD) T_c and $\bar{T}_s$ of 35.92 (0.93)°C and 23.4 (8.9)°C, respectively. Figure 2 shows a topographic distribution of the metabolic rate minus an assumed resting value of 45 $W \cdot m^{-2}$ plotted against T_c and $\bar{T}_s$. Figure 3 shows the M_{shiv} for one subject (11; see Fig. 1 for corresponding T_c and $\bar{T}_s$).

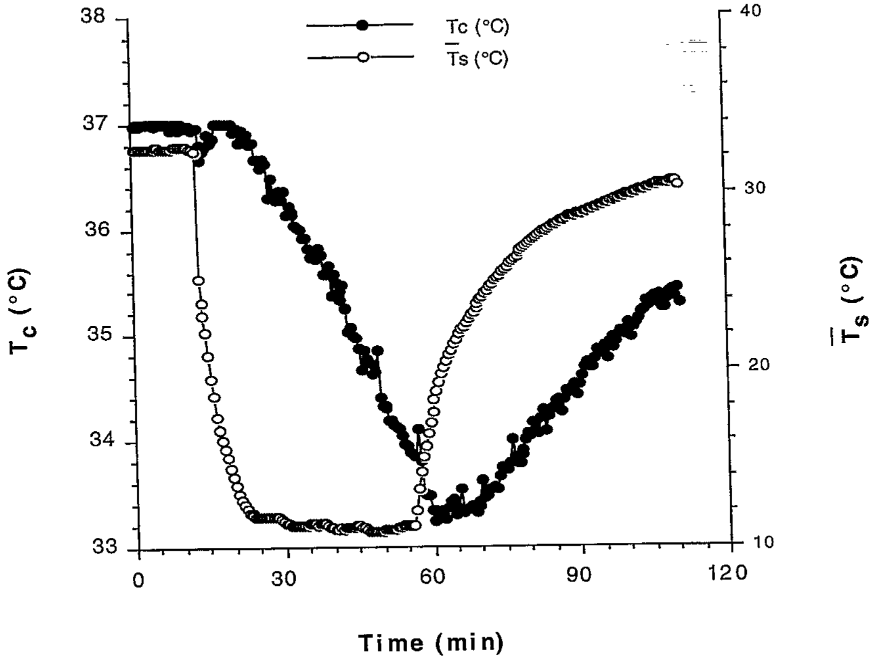
Analysis

Regressions (Dixon 1983) were first conducted on the unconstrained algebraic formulae (Eqs. 5–8) to determine which form

Table 1 Subjects' anthropometric measurements, minimum core (esophageal) temperature attained, and the core cooling time (Δt) to the minimum. (*Ht* Height, *BM* body mass, *SA* body surface area, *BF* body fat, $T_{c,min}$ minimum core temperature)

Subject no.	Age (years)	Ht (m)	BM (kg)	SA (m^2)	BF (%)	$T_{c,min}$ (°C)	Δt (min)
01	32	1.83	79.0	2.01	23.9	34.84	70.0
02	21	1.76	83.5	2.03	16.4	35.73	80.5
03	23	1.66	73.3	1.86	21.5	34.78	86.5
04	36	1.79	66.4	1.82	15.5	33.80	54.5
05	28	1.80	75.5	1.95	21.7	33.91	78.0
06	30	1.77	89.0	2.11	22.1	34.54	85.5
07	37	1.83	81.5	2.04	20.8	35.28	77.0
08	25	1.84	75.6	1.97	16.3	35.73	80.5
09	22	1.71	70.5	1.84	14.1	33.90	85.0
10	34	1.67	91.0	2.08	26.7	35.25	84.0
11	29	1.80	78.0	1.98	14.3	33.25	60.5
12	23	1.77	73.8	1.91	11.5	33.72	84.5
13	30	1.80	71.0	1.89	19.0	34.51	82.5
14	25	1.83	79.7	2.02	13.1	34.06	90.0
mean	28	1.78	77.7	1.97	18.4	34.52	78.5
(SD)	(5)	(0.06)	(6.9)	(0.09)	(4.5)	(0.78)	(9.8)

Fig. 1 Core (T_c, *closed circles*) and mean skin temperatures ($\bar{T}_s$, *open circles*) plotted against time, of subject 11 during neck-level immersion in 8°C water and subsequent self-rewarming in a dry sleeping bag



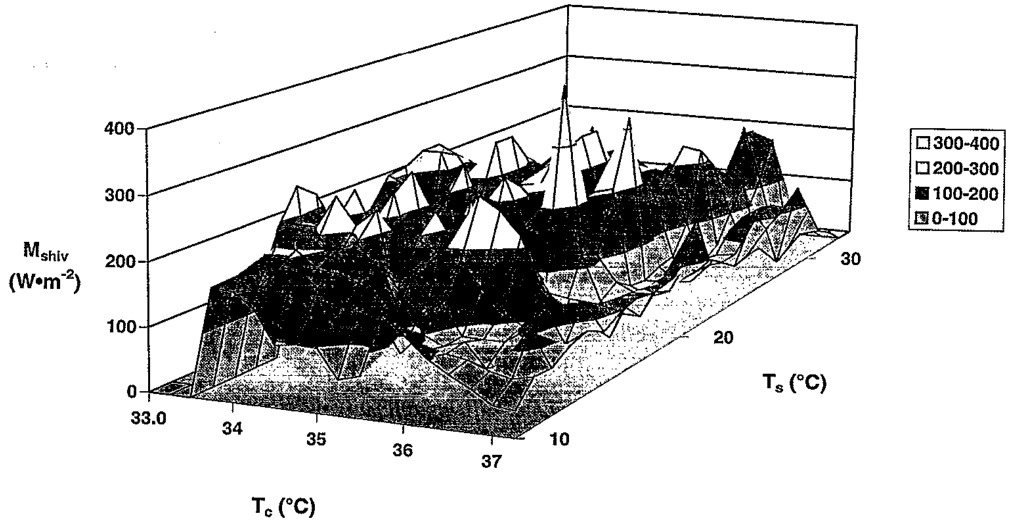


Fig. 2 Distribution of shivering metabolism (M_{shiv}; measured metabolic rate minus 45 W · m^{-2}) plotted against T_c and $\bar{T}_s$ (zero values of M_{shiv} indicate a lack of data)

best fits the uncensored data. Improvements are achieved by lowering the error between the observation and fit according to the sum of squared residuals (SSR). However, statistical significance (at the $P < 0.05$ level), and hence the best fit, was determined through the *F*-ratio test (Mekjavic and Morrison 1986). In this case, Eqs. 5–7 are considered as subsets of Eq. 8.

Regressions were then performed on the setpoint formulae using the standard setpoint temperatures of 37°C and 33°C for the core and skin, respectively. The *F*-ratio test can only be applied between Eqs. 1 and 2 since the others are independent of one another. Consequently, the decision on the best fit is simply based on the minimum value of the SSR. Once the best fit was determined, that formula was then tested against other setpoint temperatures to cover a reasonable range. These included 36.5°C and 37.5°C for the core, and 32°C and 34°C for the skin. Each formula required censored data such that temperatures above the setpoint values did not influence the shivering drive. The implicit assumption is that shivering is driven by decreases from the setpoint and is not affected by higher values (Brown and Brengelmann 1970). This includes the interaction term, which is also set to zero whenever one of the setpoint values is exceeded even if the other is not. This also ignores the possibility that a T_c above its setpoint value might inhibit shivering when $\bar{T}_s$ is below its setpoint value. We are again unable to statistically test which setpoint criteria are the best since each set, and hence formula, is applied against a different data set.

Results

All parameter estimates correspond to M_{shiv} expressed in W · m^{-2}. A fit of the simplest unconstrained equation (Eq. 5) against the uncensored data resulted in a rms error (residual mean square; rms = SSR/df, where df = degrees of freedom) of 3185. The corresponding parameter values (SD) of P'_1, P'_2, and P'_3 are 1512 (38), −37.7 (1.1), and −2.64 (0.11), respectively. Multiplying these values by the average SA of the subjects leads to respective values of 2979, −74.2, and −5.2. These values place a greater emphasis on the T_c versus $\bar{T}_s$ when compared to the values of 2324, −55.6, and −8.1 reported by Strong et al. (1985) using the same formula but normalized for SA.

Adding the quadratic term involving $\bar{T}_s$ (Eq. 6) leads to a significant improvement (rms error = 3089). In this case, the respective parameter values (SD) are 1360 (40), −35.5 (1.1), 4.45 (0.70), and −0.145 (0.014). The importance of the quadratic term is that it predicts a parabolic sensitivity of the $\bar{T}_s$ for shivering as originally reported by Benzinger (1969). In the present case, shivering intensity is maximum at a $\bar{T}_s$ of 15.3°C. However, no significant improvements were obtained by adding the interaction term in Eqs. 7 and 8 (rms error = 3182 and 3089, respectively).

Table 2 shows the parameter values for all setpoint formulae using censored data (Eqs. 1–4) with the standard setpoint temperatures of 37°C and 33°C for the core and skin, respectively. The formulae involving an interaction term (Eqs. 3 and 4) performed poorly whereas the non-interaction quadratic formula (Eq. 2) performed best (significantly better than Eq. 1) and was subsequently used to test various setpoint combinations.

The best fits for both the unconstrained and constrained formulae were obtained with a quadratic term

Table 2 Parameter (P_i, i = 1,2,3) estimates (SD) for shivering metabolism (M_{shiv}) expressed in W · m^{-2}, the root mean square (rms) error, and the degrees of freedom (df) for the setpoint formulae using the standard setpoint temperatures ($T_{c,set}$ = 37°C and $T_{s,set}$ = 33°C)

Eq	P_1	P_2	P_3	rms	df
1	48.3 (0.9)	3.73 (0.10)	–	3355	3340
2	41.0 (1.0)	9.87 (0.42)	−0.313 (0.021)	3142	3339
3	2.86 (0.11)	3.99 (0.15)	–	5158	3340
4	3.91 (0.11)	0.119 (0.008)	–	5855	3340

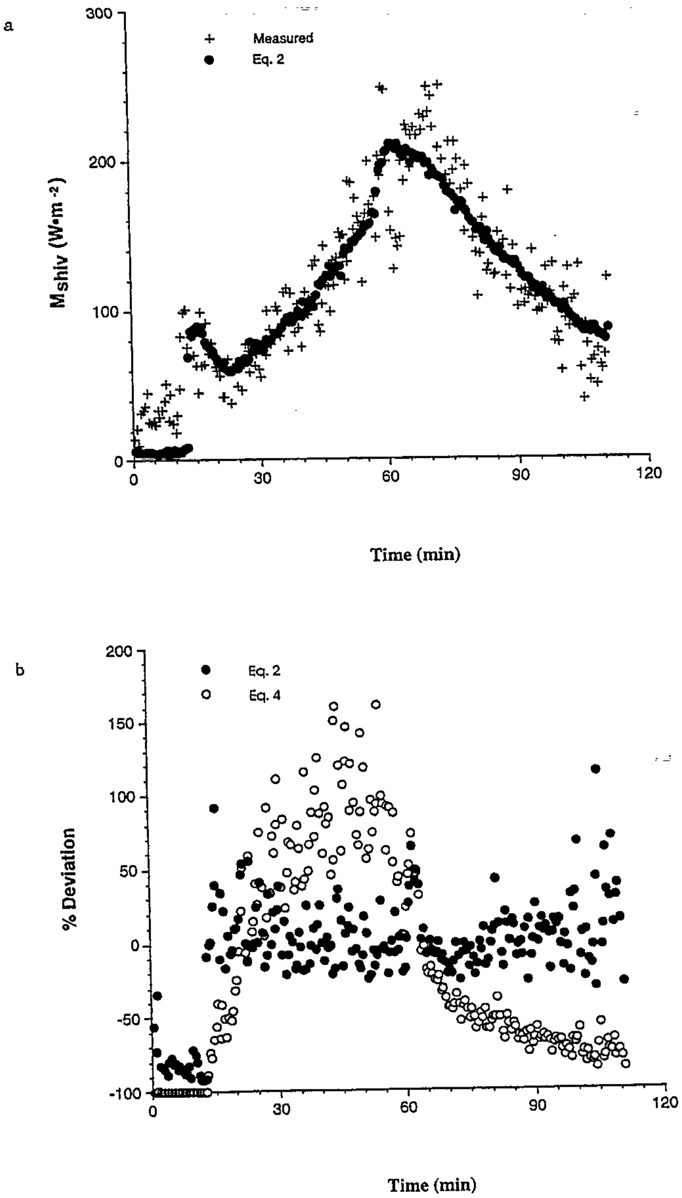


Fig. 3a,b **a** Comparison of the measured (*plus signs*) and predicted (using Eq. 2 *closed circles*) M_{shiv} of subject 11. **b** Comparison of the percent deviation (predicted minus measured) of subject 11 between predictions of Eqs. 2 (*closed circles*) and 4 (*open circles*) where the group root mean square values are 3142 and 5855, respectively

involving $\bar{T}_s$ and without any interaction term between the T_c and $\bar{T}_s$. However, no statistical comparison can be made between these two types of formulae (Eqs. 2 and 6) despite the lower rms error of the unconstrained version, since different data sets were applied in each case.

To illustrate the accuracy of the model prediction and to obtain a sense of the rms error involved, a plot of the observed and predicted M_{shiv} is shown in Fig. 3 for subject 11 (refer to Table 1 and Fig. 1). Also shown is the percent deviation between the observed and predicted M_{shiv} using Eqs. 2 and 4, which represent the best and worst fits (rms = 3142 and 5855, respectively). Note that the error obtained when using Eq. 2 is much more uniformly distributed compared to that obtained when using Eq. 4, which indicates an overprediction during cooling and an underprediction during rewarming. Non-uniformity in the prediction was also reported by Mekjavic and Morrison (1986) who tested several formulae, but none that explicitly contained a quadratic term involving $\bar{T}_s$.

Table 3 shows the parameter estimates for Eq. 2 using different setpoint temperature combinations. Since the censored data were different in each case, no rigorous statistical comparison can be made between the fits. The apparent trend, however, is that the rms error decreases as either $T_{\text{s,set}}$ increases for a given value of $T_{\text{c,set}}$, or $T_{\text{c,set}}$ increases for a given value of $T_{\text{s,set}}$. It is not certain whether this is a consequence of the mathematical manipulation or of physiological significance since increases in the setpoint values bring different data into the analysis.

Figure 4 shows a plot of Eq. 2 using the standard setpoint temperatures. In general, M_{shiv} increases as T_c decreases and, in this case, reaches a maximum when the $\bar{T}_s$ is at 17.2°C [determined from $T_{\text{s,set}} + P_2/(2 \cdot P_3)$, which is obtained by differentiating Eq. 2 and setting the result to zero].

Discussion

Through a series of carefully conducted measurements of the tympanic temperature and $\bar{T}_s$, and the $\dot{V}O_2$ of one individual immersed in water, Benzinger (1969) observed a very distinct pattern of metabolic response that is

Table 3 Parameter estimates (SD) for M_{shiv} expressed in $W \cdot m^{-2}$ and the rms error for Eq. 2 using various setpoint temperatures; the df is 3339 in each case

$T_{\text{c,set}}$	$T_{\text{s,set}}$	P_1	P_2	P_3	rms
36.5	32.0	50.8 (1.3)	11.7 (0.4)	−0.389 (0.023)	3375
36.5	33.0	48.3 (1.3)	11.4 (0.4)	−0.361 (0.021)	3289
36.5	34.0	46.5 (1.3)	10.8 (0.4)	−0.323 (0.019)	3229
37.0	32.0	42.8 (1.0)	10.1 (0.4)	−0.335 (0.023)	3224
37.0[a]	33.0[a]	41.0 (1.0)	9.87 (0.42)	−0.313 (0.021)	3142
37.0	34.0	39.7 (1.0)	9.37 (0.39)	−0.280 (0.019)	3103
37.5	32.0	36.9 (0.8)	8.50 (0.46)	−0.283 (0.023)	3154
37.5	33.0	35.4 (0.9)	8.30 (0.44)	−0.262 (0.021)	3125
37.5	34.0	34.4 (0.9)	7.87 (0.42)	−0.232 (0.019)	3109

[a] Standard setpoint temperatures

similar to the present findings. Figure 5 shows a replication of Benzinger's data (assuming a resting metabolic rate of 45 W · m^{-2} and a SA of 1.9 m^2) for T_c = 36.2°C, 36.5°C and 36.8°C. Also shown is the predicted M_{shiv} based on the best fit of all the Benzinger data (T_c range from 36.2°C to 37.0°C) using Eq. 2 with the standard setpoint temperatures. Parameter estimates (SD) were P_1 = 85.9 (13.4), P_2 = 10.4 (1.4), and P_3 = −0.499 (0.082). Next, we examine how this fit compares to the results of the present study.

Fig. 4 Fit of the M_{shiv} data plotted against T_c and $\bar{T}_s$ using Eq. 2 and setpoint temperatures of 37°C and 33°C for the core and skin, respectively

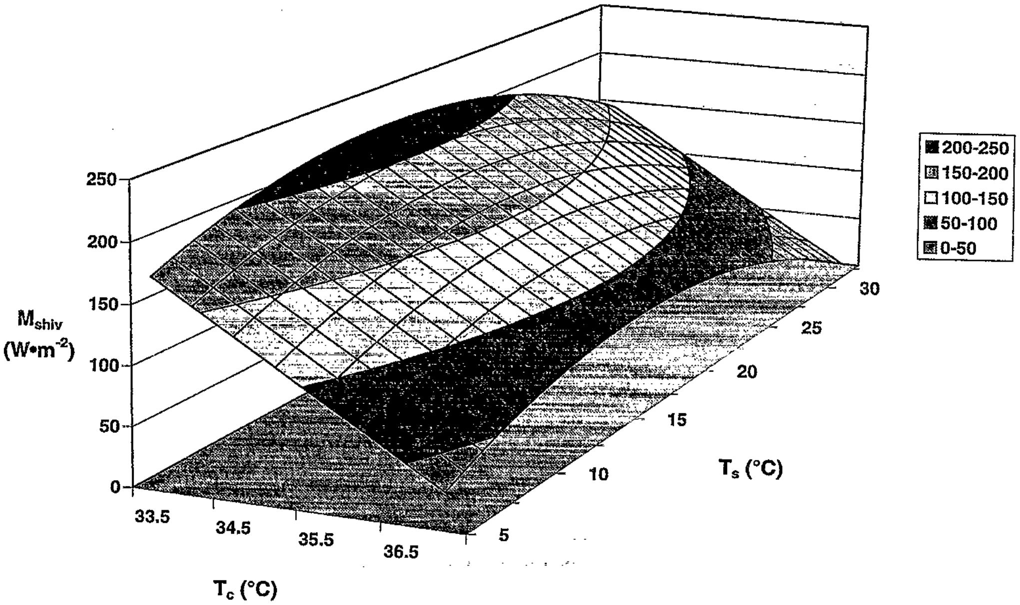


Fig. 5 Comparison of the Benzinger (1969) data (*meas*) of M_{shiv} for T_c of 36.2°C, 36.5°C, and 36.8°C plotted against $\bar{T}_s$ with the fit (*pred*) of all of the Benzinger data using Eq. 2 and setpoint temperatures of 37°C and 33°C for the core and skin, respectively

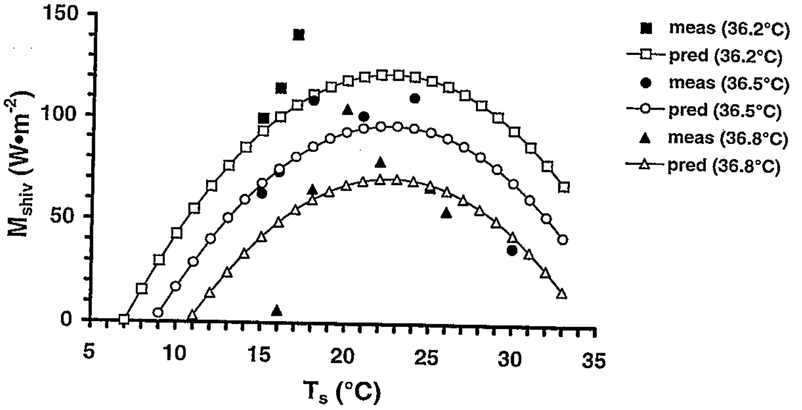


Fig. 6 Fits of M_{shiv} plotted against $\bar{T}_s$ for each subject separately using Eq. 2 and setpoint temperatures of 37°C and 33°C for the core and skin, respectively, shown for a T_c of 36.5°C. Superimposed are the fits for the pooled data and the Benzinger data (1969)

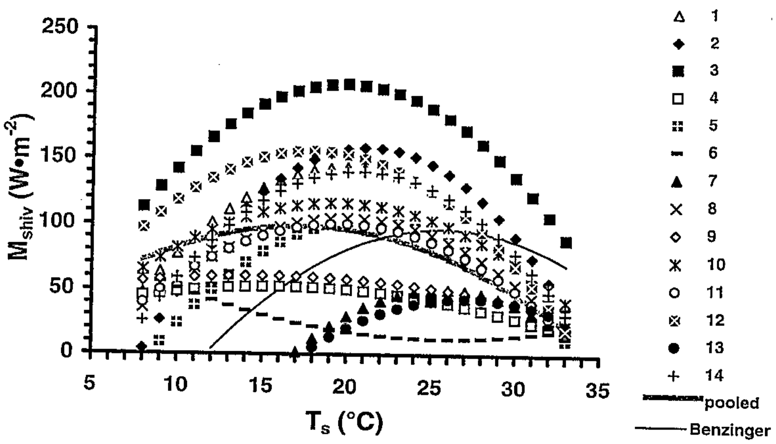


Figure 6 shows the predicted M_{shiv} of all of the subjects in the present study based on the fits of Eq. 2 to their data individually, and censored with the standard temperature setpoints. A fixed T_c of 36.5°C was chosen for this display since it approximates the midpoint of the T_c range used by Benzinger (1969). In all but one case, M_{shiv} is parabolic downwards against $\bar{T}_s$ with maxima occurring at values in the range of 12–27°C. Superimposed on this figure are the best fits using the pooled data of all subjects and the best fit of the Benzinger data. The latter falls well within the range of our subjects. Differences are primarily in the degree of parabolicity and where the maximal sensitivity of $\bar{T}_s$ occurs.

Clearly, the nature of quadratic functions such as Eq. 2 render them unsuitable for gross extrapolation. Predictions of negative M_{shiv} occur when the function is applied outside the range of data used to estimate the function parameters. This is especially noticeable in the case of two subjects (07 and 13) where negative values are predicted for $\bar{T}_s$ less than 17°C. However, close inspection of these subjects' data reveals that their respective minimum $\bar{T}_s$ were 18.2°C and 19.3°C (highest among all of the subjects), and therefore a quadratic fit to these data led to a sharper decline in M_{shiv} as $\bar{T}_s$ decreases. This illustrates that the formulae applied here are descriptive only and have a predictive value only within the range of data analyzed.

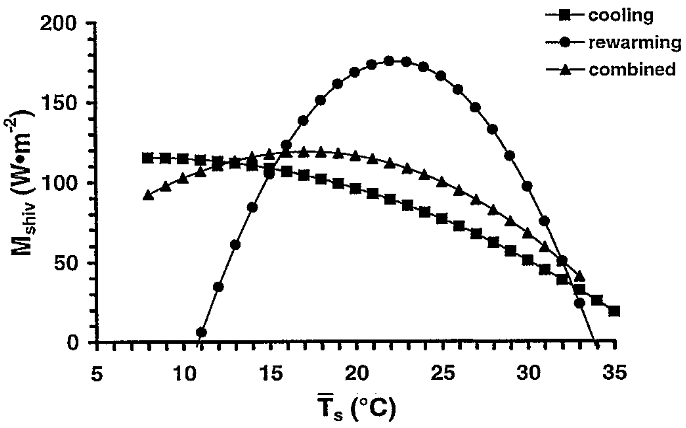


Fig. 7 Fits of M_{shiv} plotted against $\bar{T}_s$ for the pooled data during cooling, rewarming, and combined, using Eq. 2 and setpoint temperatures of 37°C and 33°C for the core and skin, respectively, shown for a T_c of 36.0°C

The lack of predictive improvement with the inclusion of a multiplicative interaction term between T_c and $\bar{T}_s$ (Eqs. 3, 4, 7, and 8) was unexpected. Previously, such a term was found necessary for improvements in fit in a number of studies (Hayward et al. 1977; Nadel et al. 1970; Stolwijk and Hardy 1966; Tikuisis et al. 1988; Wissler 1985). However, in some of these cases, the data were limited by smaller decreases in T_c and $\bar{T}_s$ than were used here. The present finding suggests that the shivering commands from central and cutaneous thermosensors are not necessarily interdependent. Previously, the signal from the core was suppressed whenever the $\bar{T}_s$ was above its setpoint value. This constraint is not supported by the present analysis of the data where shivering was observed during rewarming when the $\bar{T}_s$ exceeded 35°C.

If setpoint temperatures are deemed acceptable for modeling purposes, then a choice must be made of their optimal values. This study has been biased towards the values of 37°C and 33°C for the core and skin, respectively. Using other values have not led to unequivocal improvements in fit, except perhaps where the $\bar{T}_s$ setpoint was raised to 34°C. However, there is no statistical basis for changing the present bias since the data sets used in these determinations were different. Furthermore, the rms errors did not vary markedly.

The analysis thus far has used the pooled data of the cooling and rewarming phases. It would be instructive to examine whether differences occur in the thermogenic drive during these two phases considered separately. Data were divided according to the lowest T_c attained, which included the afterdrop in both groups, and were censored using the standard setpoint temperatures. Thus, the cooling and rewarming data contained 2035 and 1321 observations, respectively, and were case-weighted as before. Parameter estimates (SD) for Eq. 2 were $P_1 = 32.5$ (1.4), $P_2 = 6.60$ (0.43), and $P_3 = -0.132$ (0.021) during cooling and $P_1 = 23.7$ (1.8), $P_2 = 28.4$ (1.3), and $P_3 = -1.33$ (0.11) during rewarming; these fits are statistically different from each other. Figure 7 shows a plot of these fits against $\bar{T}_s$ for a T_c of 36°C (close to the mean of all of the data). The sensitivity of $\bar{T}_s$ to cooling is considerably less than during rewarming. Although both fits tend to converge at high $\bar{T}_s$, there is a marked divergence at low values. This can be partly attributed to the nature of the data used in these fits. In the case of cooling, the minimum and mean (SD) $\bar{T}_s$ were 10.2 and 18.1 (6.5)°C, respectively, which contrasts sharply with the higher values of

Table 4 Parameter estimates (SD) for M_{shiv} expressed in W · m^{-2} and the rms error for Eq. 11 using the standard setpoint temperatures ($T_{c,\text{set}}$ = 37°C and $T_{s,\text{set}}$ = 33°C). Significance (sig) indicates an improvement in fit using the anthropometric variable (SA in m^2; BM in kg; BF in %; body mass index, BMI, in kg · m^{-2})

Variable	P_1	P_2	P_3	P_4	rms	sig
SA	53.0 (7.1)	13.1 (2.0)	−0.417 (0.066)	−0.399 (0.205)	3138	no
BM	17.9 (8.5)	4.21 (2.06)	−0.133 (0.066)	0.194 (0.111)	3139	no
BF	141 (15)	41.8 (5.3)	−1.39 (0.19)	−0.462 (0.039)	3030	$P < 0.05$
BMI	3.35 (0.90)	0.748 (0.210)	−0.0241 (0.0068)	0.798 (0.085)	3058	$P < 0.05$

16.6 and 29.7 (3.5)°C, respectively, during rewarming. Consequently, the rewarming fit is poorly represented at low $\bar{T}_s$. T_c values, on the other hand, were much closer [36.1 (0.9)°C and 35.6 (0.8)°C, respectively]. Overall, we consider that the fit obtained through the combined data of cooling and rewarming provides a reasonable approximation for general predictive purposes.

Several investigators have introduced anthropometric variables to improve the prediction of M_{shiv}. These include SA (Timbal et al. 1976), BM (Hayward et al. 1977), and BF (Tikuisis et al. 1988). These and the body mass index (BMI = BM/height^2) were applied separately as multiplicative factors to Eq. 2 to determine if the fit can be further improved, as follows:

$$M_{\text{shiv}} = [P_1 \cdot (T_{\text{c,set}} - T_c) + P_2 \cdot (T_{\text{s,set}} - \bar{T}_s) + P_3 \cdot (T_{\text{s,set}} - \bar{T}_s)^2] \cdot VAR^{P_4} \tag{11}$$

where VAR is the anthropometric variable. Note that when $P_4 = 0$, the original form of Eq. 2 is recovered; hence, a statistical comparison can be applied to test for predictive improvement. Table 4 lists the results of the various fits using censored data with the standard set-point temperatures. The additions of SA and BM did not lead to significant improvements in fit, whereas BF did. Also, the negative exponent of BF verifies an earlier finding that this parameter attenuates the shivering response (Tikuisis et al. 1988). That the addition of BMI also led to an improvement, but not as great, was expected given that BMI is correlated to BF (Keys et al. 1972). For convenience, the value of P_4 was set to −0.5 for VAR = %BF and the resultant fit (rms error = 3030) was:

$$M_{\text{shiv}} = \frac{155.5 \cdot (37 - T_c) + 47.0 \cdot (33 - \bar{T}_s) - 1.57 \cdot (33 - \bar{T}_s)^2}{\sqrt{\%BF}} \tag{12}$$

The present findings confirm the original conclusion of Benzinger (1969) that the sensitivity of $\bar{T}_s$ for thermogenesis varies parabolically, in the present case peaking at about 17°C. This confirmation is remarkable considering that the data used by Benzinger involved only one subject whose T_c range was quite narrow and far from a hypothermic condition. Yet, it is consistent with the non-linear sensitivity of the cold receptors as reviewed by Hensel (1981). The present analysis, however, is also far from complete since the predictive equations are descriptive and not suitable for extrapolation beyond the measured body temperatures. Further, the predicted increase in M_{shiv} is monotonic with a decrease in T_c whereas it is known that M_{shiv} diminishes once the T_c falls below 30°C (Bristow and Giesbrecht 1988). Data are presently insufficient to complete such an analysis. In the interim, Eqs. 2 and 12 may be useful for predicting the M_{shiv} of individuals whose body temperatures fall within the ranges used in this study.

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