Estimating changes in volume-weighted mean body temperature using thermometry with an individualized correction factor

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Abstract: This study investigated whether the estimation error of volume-weighted mean body temperature ($\Delta \bar{T}_b$) using changes in core and skin temperature can be accounted for using personal and environmental parameters. Whole-body calorimetry was used to directly measure $\Delta \bar{T}_b$ in an experimental group (EG) of 36 participants (24 male(M), 12 female(F)) and a validation group (VG) of 20 (9M, 11F) throughout 90-min of cycle ergometry at 40°C, 30% RH (n=9EG, 5VG); 30°C, 30% RH (n=9EG, 5VG); 30°C, 60% RH (n=9EG, 5VG) and 24°C, 30%RH (n=9EG, 5VG). The “core” of the two-compartment thermometry model was represented by rectal temperature ($T_{re}$) and the “shell” by a 12-point mean skin temperature ($T_{sk}$). The estimation error ($X_0$) between $\Delta \bar{T}_b$ from calorimetry and $\Delta \bar{T}_b$ from thermometry using core/shell weightings of 0.66/0.34, 0.79/0.21 and 0.90/0.10 was calculated after 30, 60 and 90-min of exercise. The association between $X_0$ and the individual variation in metabolic heat production (M-W), body surface area (BSA), body fat percentage (%fat) and body surface area-to-mass ratio (BSA/BM), as well as differences in environmental conditions (Oxford index) in the EG data was assessed using stepwise linear regression. At all time points and with all core/shell weightings tested, M-W, BSA and Oxford index independently correlated significantly with the residual variance in $X_0$, but %fat and BSA/BM did not. The subsequent regression models were used to predict the thermometric estimation error ($X_{0,\text{pred}}$) for each individual in the VG. The value estimated for $X_{0,\text{pred}}$ was then added to the $\Delta \bar{T}_b$ estimated using the two-compartment thermometry models yielding an adjusted estimation ($\Delta \bar{T}_{b,\text{adj}}$) for the individuals in the VG. When comparing $\Delta \bar{T}_{b,\text{adj}}$ to the $\Delta \bar{T}_b$.
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derived from calorimetry in the VG, the best performing model used a core/shell
weighting of 0.66/0.34 describing 74%, 84% and 82% of the variation observed in \( \Delta \bar{T}_b \)
from calorimetry after 30, 60 and 90-min respectively.

**Keywords:** body heat storage; calorimetry, core temperature, heat stress, skin
temperature
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Introduction

For the past 70 years the two-compartment thermometry model of “core” and “shell” has been widely used as a method to express the thermal state of an individual in terms of changes in volume-weighted body temperature, otherwise known as the change in mean body temperature ($\Delta \overline{T}_b$) (3). In addition, changes in body heat content ($\Delta H_b$) have been subsequently estimated using the product of $\Delta \overline{T}_b$, total body mass and the average specific heat of the tissues of the body (8). These two variables have been used extensively in the literature, firstly as a means to evaluate treatment methods for the avoidance and/or alleviation of heat stress (15, 20, 36); and also as central mechanistic components of behavioral and physiological control of exercise/work output in hot environments (1, 2, 22, 31).

Much research has focused upon deriving the optimal sum-to-one weighting coefficients of the “core” and “shell” compartments for the accurate estimation of $\Delta \overline{T}_b$ and therefore $\Delta H_b$; with typical core/shell weightings in a hot environment ranging from 0.95/0.05 (29, 30) and 0.79/0.21 (6) to 0.66/0.34 (11). A recent study from our own laboratory (18) used direct and indirect calorimetry to calibrate the 2-compartment model for $\Delta \overline{T}_b$ deriving the best-fitting core/shell weightings during both transient and steady-state body temperatures. However, even when using three different measures of core temperature (rectal, esophageal and aural canal) and employing the optimal core/shell weightings for the specific individuals under the exact conditions of the study, a
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systematic underestimation of $\Delta T_b$ always occurred (18, 26). This confirmed earlier studies suggesting that thermometric models did not accurately estimate $\Delta H_b$ (13, 28, 32).

A potential solution for the underestimation of $\Delta T_b$ is the addition of a mathematical constant or “correction factor” (5, 6). While this approach provides an improved estimation, a generic correction factor employed with the best-fitting core/shell weightings has been shown to only account for ~50% of the variation observed in $\Delta T_b$ during exercise in warm environments (18). Since whole-body calorimeters are not widespread and thermometry is a relatively straightforward technique employed in laboratories around the world, further research is required to improve the predictive power of thermometric models for estimating changes in $\Delta T_b$ and therefore $\Delta H_b$. One possible approach may be to employ the conventional fixed core/shell weightings for the two-compartment thermometry model of $\Delta T_b$ and then derive a model to predict the correction value required for each individual. While this method may not unveil the underlying mechanism that causes the conventional two-compartment thermometry model to underestimate $\Delta T_b$, it may point to a practical model whereby the association of particular environmental and physical characteristics with magnitude of underestimation of $\Delta T_b$ can be used as predictors. As such, this is not proposed as an ultimate solution, rather an exploration of potential avenues for improving the estimation of $\Delta T_b$ using core and skin temperatures.
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Our previous calorimetry work has shown that the absolute estimation error of the conventional thermometric approach for $\Delta \bar{T}_b$ during exercise in warm environments becomes greater with increasing heat storage (17, 18). A method accounting for the characteristics of the individual that influence body heat storage may therefore provide an improved estimation of $\Delta \bar{T}_b$ using core/shell thermometry model. Body surface area determines the interface for heat exchange with the environment and its ratio relative to body mass can influence the magnitude of core temperature elevation in a given environment (14). Furthermore, body fat theoretically behaves as a barrier to conductive heat exchange between the body core and shell; a greater percentage body fat may therefore cause a smaller increase in shell (skin) temperature for a given $\Delta H_b$. In addition both metabolic heat production and environmental parameters greatly influence $\Delta H_b$ during exercise (4).

The aim of this study was to derive a model to predict an individualized correction value to be used with the conventional two-compartment thermometry approach for the estimation of the change in mean body temperature during exercise in the heat. It was hypothesized that the underestimation of the change in mean body temperature using the two-compartment model increases with increasing metabolic heat production and ambient temperature/humidity, but decreases with increasing body surface area, surface area-to-mass ratio and body fat percentage. It is also hypothesized that the consideration of these parameters would significantly improve the predictive power of the two-compartment model.
Methods

Participants

Following approval of the experimental protocol from the University of Ottawa Research Ethics Committee and obtaining written informed consent, an experimental group (EG) of 36 (24 males, 12 females) and a validation group (VG) of 20 (9 males, 11 females) volunteered for the study. All participants were healthy, non-smoking and normotensive. Participants were distributed across the environmental conditions of 40ºC, 30% RH (n=9EG, 5VG); 30ºC, 30% RH (n=9EG, 5VG); 30ºC, 60% RH (n=9EG, 5VG); and 24ºC, 30% RH (n=9EG, 5VG). The range of ambient conditions was selected to attain a useful variation in the calorimetric and thermometric measures under different heat stress conditions. Mean physical characteristics of EG and VG participants are given in Table 1.

Body composition of each participant was measured using Dual energy x-ray absorptiometry (DEXA) by which the body mass is partitioned into fat tissue mass (mf), lean tissue mass (ml), and bone mass (mb). Lean tissue mass (ml) is further subdivided into muscle mass (51.0% of ml), skin mass (11.0%) white matter, grey matter, eye, nerve, lens, and cartilage mass (12.9%), blood mass (25.0%), and cerebral spinal fluid mass (0.1%) (9, 27). Using these components, the mean specific heat of the body (Cp) was determined (10) and is given in Table 2.

Instrumentation

Thermometry:
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Rectal Temperature (\(T_{re}\)): Measured using a pediatric thermocouple probe (Mon-a-therm General Purpose Temperature Probe, Mallinckrodt Medical, St-Louis, MO, USA) inserted to a minimum of 12 cm past the sphincter.

Mean Skin Temperature (\(\bar{T}_{sk}\)): Skin temperature was measured at 12 points over the body surface using 0.3 mm diameter T-type (copper/constantan) thermocouples integrated into heat-flow sensors (Concept Engineering, Old Saybrook, CT, USA). Thermocouples were attached using porous surgical tape (Blenderm, 3M, St. Paul, MN, USA). \(\bar{T}_{sk}\) was calculated using the 12 skin temperatures weighted to the regional proportions as determined by Hardy and DuBois (12): head 7%, hand 4%, upper back 9.5%, chest 9.5%, lower back 9.5%, abdomen 9.5%, bicep 9%, forearm 7%, quadriceps 9.5%, hamstring 9.5%, front calf 8.5%, and back calf 7.5%.

All temperature data were collected using a HP Agilent data acquisition module (model 3497A) at a sampling rate of one reading every 15 s and simultaneously displayed and recorded in spreadsheet format on a personal computer (IBM ThinkCentre M50) with LabVIEW software (Version 7.0, National Instruments, TX, USA).

Indirect and Direct Calorimetry:

Change in body heat content (\(\Delta H_b\)) was measured using the temporal summation of metabolic heat production by indirect calorimetry and the net evaporative and dry heat exchange of the body with the environment by direct calorimetry. The measurement technique was identical to that described in previous publications (16-18).
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Indirect calorimetry employed the open circuit technique using expired gas samples drawn from a 6 L fluted mixing box yielding a measurement error of ±0.25% for rate of metabolic energy expenditure (M). Expired gas was analyzed using electrochemical gas analyzers (AMETEK model S-3A/1 and CD 3A, Applied Electrochemistry, Pittsburgh, PA, USA) calibrated before each trial using gas mixtures of 4% CO₂, 17% O₂, balance N₂. The turbine ventilometer was calibrated using a 3 L syringe. The rate of external work (W) measured with the cycle ergometer within the whole-body calorimeter (see below) was subtracted from the rate of metabolic energy expenditure to give the rate of metabolic heat production (M-W).

A modified Snellen direct air calorimeter was employed for the purpose of measuring whole-body changes in evaporative and dry heat loss, yielding an accuracy of ± 2.3 W for the measurement of rate of total heat loss. The calorimeter was previously calibrated for rate of dry heat loss using a humanoid manikin heat source made of constant power zone heater cable (5.905 kΩ•m⁻¹, Easy Heat ZH8-1CBR, New Castle, IN, USA); and for rate of evaporative heat loss using a precision tubing pump (Cole-Palmer, Masterflex 7550-30; Pump head 77200-50) delivering 5 ml•min⁻¹ (±0.01 mL•min⁻¹) to a heated 1200 W hotplate. A full peer-reviewed technical description of the fundamental principles and performance characteristics of the upgraded Snellen calorimeter is available (25).
Experimental Protocol

All participants volunteered for two separate testing days. On testing day 1, an incremental cycle ergometer VO₂peak test was performed. On testing day 2, the calorimetry experimental exercise protocol was performed. Testing days were separated by a minimum of 72 h. All calorimeter trials were performed at the same time of day. Participants were asked to arrive at the laboratory after eating a small breakfast (i.e. dry toast and juice), but consuming no tea or coffee that morning, and also avoiding any major thermal stimuli on their way to the laboratory. Participants were also asked to not drink alcohol or exercise for 24 h prior to experimentation.

Following instrumentation, the participant entered the calorimeter regulated at the ambient environmental conditions of dry-bulb air temperature (T_{db}) = 40.0°C, relative humidity (RH) = 30% (water vapor pressure (P_w) = 16.6 mmHg); T_{db} = 30.0°C, RH = 60% (P_w = 19.1 mmHg); T_{db} = 30.0°C, RH = 30% (P_w = 9.5 mmHg); T_{db} = 24.0°C, RH = 30% (P_w = 6.7 mmHg). The participant, in the upright seated position, rested for a 45-min stabilization period while a steady-state baseline resting condition was achieved, determined by a change in rectal temperature of ±0.1°C over the final 15-min. Subsequently, the participant cycled at 40% of their pre-determined VO₂peak for 90-min. This level of exercise intensity was selected in order to ensure that heat stress was compensable even under the warmest environmental conditions since a prerequisite for the 2-compartment model is that steady-state body temperatures occur during exercise (3). This level of exercise intensity also ensured that fatigue-induced reduction in mechanical efficiency and resultant increases in metabolic heat production did not occur.
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For all experimentation, clothing insulation was standardized at ~0.2 to 0.3 clo (i.e. cotton underwear, shorts, sports bra (for women) and sandals).

Statistical Analyses

Data were analyzed after 30, 60 and 90-min of exercise in order to investigate the performance of the thermometry models across different experimental durations.

Analyses of Experimental Group (EG)

Change in mean body temperature using calorimetry:

Change in body heat content as measured using calorimetry ($\Delta H_{b, cal}$) was solved for change in mean body temperature ($\Delta \bar{T}_{b, cal}$) after 30, 60 and 90-min of exercise using the following equation:

$$\Delta \bar{T}_{b, cal} = \frac{\Delta H_{b, cal}}{(b_m \cdot C_p)}$$

Where: $\Delta H_{b, cal}$ is change body heat content by calorimetry (in kJ), $b_m$ is total body mass (kg) and $C_p$ is specific heat of each participant as measured using DEXA (in kJ•kg$^{-1}$•°C$^{-1}$).

Two-compartment thermometry model of change in mean body temperature:

The traditional 2-compartment thermometry model (3) was used to estimate change in mean body temperature ($\Delta \bar{T}_{b, trad}$) after 30, 60 and 90-min of exercise using:

$$\Delta \bar{T}_{b, trad} = (X \cdot \Delta T_{re}) + ((1 - X) \cdot \Delta \bar{T}_{sk})$$
Where: $\Delta T_{re}$ is the change in rectal temperature and $\Delta \bar{T}_{sk}$ is the change in mean skin temperature. The value for weighting coefficient $X$ is the proportion of the body representing the body “core” and the value for $(1 - X)$ is the proportion of the body representing the body “shell”. Values for $X$ tested were the conventional values of 0.66, 0.79 and 0.90 that are typically used in the literature for individuals exercising in moderate to hot environments (6, 12, 29).

Thermometry estimation error:

The estimation error ($X_0$) of the two-compartment thermometry model for $\Delta \bar{T}_b$ relative to calorimetry was calculated for each individual after 30, 60 and 90-min using:

$$X_0 = \Delta \bar{T}_{b\text{trad}} - \Delta \bar{T}_{b\text{cal}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots
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Where: $\beta_0$ is the intercept; $\beta_1$, $\beta_2$, $\beta_3$, $\beta_4$ and $\beta_5$ are the regression coefficients representing the independent contributions of each variable to the prediction of $X_0$. Net metabolic heat production was expressed in kilojoules per minute (kJ•min$^{-1}$); body surface area was expressed meter squared (m$^2$); environmental conditions were expressed in degrees Celsius (ºC) as a weighted average of wet-bulb temperature ($T_{wb}$) and dry-bulb temperature ($T_{db}$) using the Oxford index (21, 24); body fat percentage was expressed in percentage of total body mass (%); and body surface area-to-mass ratio was expressed in square meters per kilogram of total body mass (m$^2$•kg$^{-1}$). Variables were screened for collinearity, with levels of collinearity only considered acceptable and the regression model considered stable for tolerance values greater than 0.70.

Analyses of Validation Group (VG)

Validation of regression model:

The regression model for the estimation error ($X_0$) derived from the experimental group (EG) was validated against the data obtained with the independent validation group (VG). The adjusted value for the change in mean body temperature ($\Delta \Bar{T}_{b,\text{adj}}$) was calculated using:

$$\Delta \Bar{T}_{b,\text{adj}} = \Delta \Bar{T}_{b,\text{trad}} + X_{0\text{,pred}}$$

(5)

Where: $\Delta \Bar{T}_{b,\text{trad}}$ is the change in mean body temperature estimated using the thermometry responses of the VG and the traditional two-compartment model (equation 2). The
predicted estimation error \( (X_{0,\text{pred}}) \) was calculated using the derived regression model from the EG and the variables specific to the individuals of the VG.

The predictive power of both the traditional \( (\Delta \bar{T}_{b,\text{trad}}) \) and adjusted \( (\Delta \bar{T}_{b,\text{adj}}) \) thermometry model for the change in mean body temperature in the independent VG was evaluated by comparing these values to those obtained using calorimetry in the VG. Goodness-of-fit was measured by an adapted \( R^2 \) statistic as previously described (18). The mean percentage error observed with the adjusted thermometry model relative to calorimetry was calculated with 95% confidence intervals. Since mean percentage error equates to percentage bias (23), employing 95% confidence intervals and observing if these intervals include zero is equivalent to testing to the null hypothesis that the model is unbiased at the 0.05 significance level.
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Results

Experimental group (EG)

Mean changes in rectal temperature and mean skin temperature after 30, 60 and 90-min of steady-state exercise under each environmental condition is given for the EG in Table 3. The average mean body temperature ($\Delta T_{b\_trad}$) estimated using the traditional two-compartment thermometry model and conventional core/shell weightings of 0.66/0.34, 0.79/0.21 and 0.90/0.10 are compared to the values directly measured with whole-body calorimetry ($\Delta T_{b\_cal}$) at each time point in Table 3. The mean absolute estimation error ($X_0$) between $\Delta T_{b\_trad}$ and $\Delta T_{b\_cal}$ at each environmental condition is also given for each time point in Table 3. In comparison to calorimetry, the two-compartment thermometry model systematically underestimated $\Delta T_{b}$ at all time points and under all environmental conditions irrespective of core/shell weighting. Mean percentage error was between -39.0% [-34.1, -43.8] and -49.0 % [-45.1, -52.8] after 30-min of exercise; between -35.1% [-29.5, -40.7] and -40.4% [-35.6, -45.2] after 60-min of exercise; and between -38.2% [-32.1, -44.3] and -40.9% [-35.2, -46.6] after 90-min of exercise.

Regression model for individualized correction factor using EG data

Backward step-wise multiple regression analysis showed that metabolic heat production ($\beta_1$), body surface area ($\beta_2$) and environmental conditions ($\beta_3$) significantly (P<0.05) correlated with the residual variance in $X_0$ after 30, 60 and 90-min of exercise when using each of the core/shell weightings. Body fat percentage ($\beta_4$) and body surface-
area-to-mass ratio ($\beta_5$) however did not significantly correlate with the residual variance in $X_0$ ($P>0.05$). The final models derived by regression analyses for each of the 9 (3 time-points for each of the 3 core/shell weightings) step-wise regression analyses are detailed in Table 4.

**Validation group (VG)**

A predicted correction factor ($X_{0,\text{pred}}$) to be used with the traditional thermometry model and conventional core/shell weightings was calculated for each individual in the independent validation group (VG) using the regression equations derived using the EG (Table 4) and data detailed in Table 1. The changes in mean body temperature using the unadjusted ($\Delta \bar{T}_{b,\text{trad}}$) and adjusted ($\Delta \bar{T}_{b,\text{adj}}$) thermometry model incorporating the predicted correction factor are compared to the changes in mean body temperature measured using calorimetry ($\Delta \bar{T}_{b,\text{cal}}$) for each individual in the VG after 30-min (Fig.1), 60-min (Fig.2) and 90-min (Fig. 3) respectively. At all time points and using all core/shell weightings the unadjusted thermometry model ($\Delta \bar{T}_{b,\text{trad}}$) was statistically biased ($P<0.05$), but the adjusted thermometry model ($\Delta \bar{T}_{b,\text{adj}}$) using the predicted correction factor ($X_{0,\text{pred}}$) from the regression equation derived from the EG yielded unbiased prediction at all time points irrespective of core/shell weighting (Fig.4A-C). For core/shell weightings of 0.66/0.34, 0.79/0.21 and 0.90/0.10 respectively, adjusted $R^2$ statistics were 0.74, 0.67 and 0.57 after 30-min, 0.84, 0.79 and 0.73 after 60-min, and 0.82, 0.77 and 0.70 after 90-min.
Discussion

We previously demonstrated that the traditional two-compartment thermometry model systematically underestimates the change in volume-weighted mean body temperature throughout exercise in the heat irrespective of core/shell weighting (18). When employing a fixed correction factor the estimation of mean body temperature using thermometry was no longer statistically biased, but only a maximum of ~50% of the variation observed in Δ\(\bar{T}_b\) as measured by calorimetry was explained using thermometry (18). The present study details an alternative approach. The association between the thermometric underestimation of each individual and their morphological and environmental parameters is quantified. The required correction is then estimated and subsequently used with the standard two-compartment thermometry model of “core” and “shell” temperatures measured with \(T_{re}\) and \(\bar{T}_{sk}\) respectively and the conventional core/shell weightings of 0.66/0.34, 0.79/0.21 and 0.90/0.10. Relative to the approaches detailed in our previous studies (17, 18) this approach yielded an improved estimation of Δ\(\bar{T}_b\), with a maximum of 74%, 84% and 82% of the variation in Δ\(\bar{T}_b\) as measured by calorimetry accounted for using thermometry after 30, 60 and 90-min of exercise respectively. At each time point the optimal model employed a core/shell weighting of 0.66/0.34 and the factors of environmental condition (represented by an Oxford index temperature), metabolic heat production and body surface area to estimate the correction factor required for each individual.
Regression analysis requires that collinearity does not exist between any variables within a given model. In the model tested in the present study collinearity did exist between body surface area ($\beta_2$), fat percentage ($\beta_4$) and body surface area-to-mass ratio ($\beta_5$). Indeed, all three variables significantly correlated with the residual variance observed in the estimation error ($X_0$) between $\Delta \bar{T}_{b,\text{trad}}$ and $\Delta \bar{T}_{b,\text{cal}}$ at all time points and using all core/shell weightings when included in the model in isolation of each other. However body surface area was included ahead of body fat percentage and body surface area-to-mass ratio in the final models since this variable consistently had a greater partial correlation coefficient and greater significance.

Environmental conditions were characterized using the Oxford index (21, 24) allowing ambient air temperature and humidity to be expressed as a single value. This facilitated the consideration of environmental influences upon both dry heat exchange and evaporative heat loss. The Oxford index was preferred ahead of the more commonly used wet-bulb globe temperature (WBGT) index (24) since no significant source of ambient radiation was present; however this limits the use of the proposed models to environments where no significant radiant heat source is present. The estimation error of the two-compartment thermometry model relative to calorimetry increased with increasing Oxford index temperature. Starting mean skin temperatures were lower at the cooler environmental conditions, resulting in a smaller change in “shell” temperature throughout exercise in the warmer environmental conditions despite greater changes in body heat content. Using an indicator of environmental condition (Oxford index) to predict $X_0$ therefore possibly account for this source of underestimation.
The individual rate of metabolic heat production also significantly correlated with the residual variance in $X_0$. Since a greater local thermogenesis of the working muscles would have occurred at greater rates of metabolic heat production, active muscle temperature and therefore local heat storage in working muscle tissue would also have been greater (33). However other than conductive heat transfer from muscle tissue to the body “core” or convective heat transfer to the body “shell” via the circulatory system, the heat storage in muscle would not be directly reflected by changes in either component of the two-compartment model. This is equivalent to saying that the consistent underestimation of $\Delta T_b$ is caused by the omission of change in muscle temperature. Indeed, a previous study of a 3-compartment model that included change in muscle temperature (17) removed statistical bias but only explained ~50% of the variation in $\Delta T_b$. Much of the remaining variability may have come from the variability of metabolic heat production (i.e. $M - W$) when participants worked at ~40% of their peak oxygen consumption, which itself varied widely due to differences in aerobic fitness. Such variability would make $M - W$ equally as variable.

Body surface area of the individual negatively correlated with the residual variance in $X_0$ and described variation in the data that was not accounted for by metabolic heat production or environmental condition. The finding that $X_0$ was greater in individuals with a smaller body surface may be due to the fact that at a given local sweat rate, absolute evaporative heat loss (in Watts) will be less with a smaller surface area. If
the proportional control between core temperature and local sweat rate (34) is the same between two individuals of different surface area, the rate of heat storage at a set metabolic heat production will be greater in the person with a smaller surface area. A possible explanation for the finding that body fat percentage did not correlate significantly with X₀ (once the residual variance explained by body surface area had been accounted for) is that fat does not necessarily impede heat transfer from the body core to the shell during hyperthermia. Elevations in skin blood flow reduce mean tissue insulation by between 4 to 6 times relative to rest (24); therefore conductive heat transfer resistance from subcutaneous fat layers would likely be rendered inconsequential.

In all of the regression equations derived for estimating the individualized value for X₀ a constant (β₀) is included despite non-significance. When a constant is omitted from a regression model, the statistical package used for the analyses of the data (SYSTAT) reverts to a default formula that calculates R-squared using: \[ R^2 = 1 - \left( \frac{\text{residual sum of squares}}{\text{total sum of squares about zero}} \right). \] A large variation around zero will therefore cause the second term in this equation to be small, ultimately yielding an R-squared value that is erroneously close to 1 despite a large amount of variation in the data (19). A constant was therefore included in all models.

Caution should be used when interpreting the meaning of the change in mean body temperature (Δ\( \overline{T}_b \)) derived using the two-compartment thermometry model of “core” and “shell”. The role of Δ\( \overline{T}_b \) in the present study is a volume-weighted temperature to be used for the estimation of body heat storage. The two-compartment
model was actually initially developed as a forcing function to express the relative influence of central and peripheral thermal drive upon thermoregulatory effector responses such as sweating, vasodilatation/constriction and shivering (34, 35). The use of $\Delta \bar{T}_b$ in this context is not disputed, and the adjustments recommended in this and other studies published on this topic by our research group (17, 18) should only be applied to instances where thermometry is used to estimate changes in body heat storage.

A limitation to the present study is the lack of balance between sexes in the groups at each environmental condition. While the mean value and variation of physical characteristics is similar between environmental groups, a perfectly normal distribution of these values is not obtained for fat mass and lean mass. However the residuals of each of the independent variables in each of the models derived for the experimental group were screened (visual inspection) for homoscedasticity. As indicated earlier, the purpose of this study is not necessarily to identify a cause and effect between individual and environmental parameters and the magnitude of underestimation for $\Delta \bar{T}_b$. Rather, the aim was use the knowledge from our previous studies that $X_0$ increased with increasing heat storage (17, 18) and exploit the association of particular parameters with $\Delta \bar{T}_b$ to allow the estimation of $X_0$. Further studies are needed to identify the underlying physiological cause for the thermometric underestimation of $\Delta \bar{T}_b$. In terms of reducing the estimation error further under a greater range of conditions than those investigated in the present study, other personal factors that influence the magnitude of body heat storage and therefore the estimation error of the two-compartment thermometric model should be
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considered. Among these are the onset threshold thermosensitivity, and maximum capacity of sweating of the individual since these physiological features greatly determine evaporative heat loss, the most prominent heat loss component during exercise in the heat.

Practical Implications

The implications of this study are that the chronic underestimation of body heat storage using the classic thermometric approach could at least be partially accounted for by incorporating factors that determine the individual variability in the rates of heat production and heat exchange with the environment. While the equations provided do not cover all individuals, activities and environments these findings suggest that thermometric estimations of heat storage under such circumstances could be significantly improved in a similar manner.

In conclusion, the validation of the regression equations reported in this article demonstrate that the underestimation of the traditional two-compartment thermometry model for the change in mean body temperature using conventional core/shell weightings can be significantly improved when accounting for individual characteristics and simple environmental parameters. However, the use of these equations should be limited to light-to moderate exercise intensities (~40% of VO$_{2\text{peak}}$) during cycling and under the modest range of environmental conditions tested in this study.
Acknowledgements

This research was supported by the U.S. Army Medical Research and Material Command’s Office of the Congressionally Directed Medical Research Programs and Natural Sciences and Engineering Research Council. (Grants held by Dr. Glen Kenny; gkenny@uottawa.ca). We would also like to thank Daniel Gagnon, Erin Kelly, Lindsay Nettlefold and Louise Gareipy for their assistance during data collection; and Dr. Tim Ramsay for his advice when performing the statistical analyses.
References


Estimating changes in mean body temperature


Estimating changes in mean body temperature


Estimating changes in mean body temperature


Table 1. Mean descriptive characteristics for participants in the experimental group (EG) and the validation group (VG).

<table>
<thead>
<tr>
<th>Ta (ºC)</th>
<th>RH (%)</th>
<th>Oxford Index (ºC)</th>
<th>Body mass (kg)</th>
<th>BSA (m²)</th>
<th>Heat production (kJ/min)</th>
<th>( \dot{V}O_{2\text{peak}} ) (mL/kg/min)</th>
</tr>
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<tbody>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>(TBM)</td>
</tr>
<tr>
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<td>29</td>
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<td>1.85</td>
<td>25.4</td>
<td>50.4</td>
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<td>n=9</td>
<td>(9.3)</td>
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<td>(6.4)</td>
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<td>(9.7)</td>
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<td>1.93</td>
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<td>53.2</td>
<td>68.8</td>
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<td>(0.24)</td>
<td>(3.8)</td>
<td>(7.3)</td>
<td>(5.1)</td>
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<table>
<thead>
<tr>
<th>Ta (ºC)</th>
<th>RH (%)</th>
<th>Oxford Index (ºC)</th>
<th>Body mass (kg)</th>
<th>BSA (m²)</th>
<th>Heat production (kJ/min)</th>
<th>( \dot{V}O_{2\text{peak}} ) (mL/kg/min)</th>
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<td>43.3</td>
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<tr>
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<td>(7.3)</td>
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<tr>
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<td>(0.16)</td>
<td>(4.0)</td>
<td>(5.8)</td>
<td>(10.5)</td>
</tr>
<tr>
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<td>19</td>
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<td>1.85</td>
<td>26.0</td>
<td>43.3</td>
<td>55.4</td>
</tr>
<tr>
<td>30</td>
<td>n=5</td>
<td>(23.8)</td>
<td>(0.37)</td>
<td>(10.4)</td>
<td>(9.9)</td>
<td>(8.5)</td>
</tr>
<tr>
<td>24</td>
<td>15</td>
<td>73.1</td>
<td>1.85</td>
<td>24.9</td>
<td>47.1</td>
<td>61.9</td>
</tr>
<tr>
<td>30</td>
<td>n=5</td>
<td>(10.3)</td>
<td>(0.16)</td>
<td>(5.6)</td>
<td>(7.7)</td>
<td>(8.0)</td>
</tr>
</tbody>
</table>

Ta: ambient temperature; RH: relative humidity. Oxford Index calculated using 0.85\( t_{\text{wb}} \) + 0.15\( t_{\text{db}} \) where \( t_{\text{wb}} \) and \( t_{\text{db}} \) are the wet and dry bulb temperature respectively. Body Surface Area (BSA) estimated using the equation of DuBois and DuBois (7), volume of peak oxygen consumption (\( \dot{V}O_{2\text{peak}} \)) expressed per kilogram of total body mass (TBM) and per kilogram of lean body mass (LBM). Values given are means and standard deviation (in parentheses).
Estimating changes in mean body temperature

Table 2. Mean body composition dual energy x-ray absorptiometry (DEXA) results for participants in the experimental group (EG) and the validation group (VG).

<table>
<thead>
<tr>
<th>Ta RH</th>
<th>Oxford Index (ºC)</th>
<th>Lean mass (kg)</th>
<th>Fat mass (kg)</th>
<th>C&lt;sub&gt;p&lt;/sub&gt; (kJ/kg/ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30ºC</td>
<td>29</td>
<td>56.6</td>
<td>10.9</td>
<td>3.49</td>
</tr>
<tr>
<td>60% n=9</td>
<td>(5.0)</td>
<td>(6.2)</td>
<td>(0.05)</td>
<td></td>
</tr>
<tr>
<td>40ºC</td>
<td>25</td>
<td>54.8</td>
<td>13.5</td>
<td>3.47</td>
</tr>
<tr>
<td>30% n=9</td>
<td>(8.3)</td>
<td>(5.8)</td>
<td>(0.05)</td>
<td></td>
</tr>
<tr>
<td>30ºC</td>
<td>19</td>
<td>50.1</td>
<td>16.2</td>
<td>3.46</td>
</tr>
<tr>
<td>30% n=9</td>
<td>(9.5)</td>
<td>(7.7)</td>
<td>(0.05)</td>
<td></td>
</tr>
<tr>
<td>24ºC</td>
<td>15</td>
<td>58.2</td>
<td>15.6</td>
<td>3.47</td>
</tr>
<tr>
<td>30% n=9</td>
<td>(7.3)</td>
<td>(9.6)</td>
<td>(0.06)</td>
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</tr>
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</table>

<table>
<thead>
<tr>
<th>Ta RH</th>
<th>Oxford Index (ºC)</th>
<th>Lean mass (kg)</th>
<th>Fat mass (kg)</th>
<th>C&lt;sub&gt;p&lt;/sub&gt; (kJ/kg/ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30ºC</td>
<td>29</td>
<td>49.6</td>
<td>17.3</td>
<td>3.42</td>
</tr>
<tr>
<td>60% n=5</td>
<td>(12.8)</td>
<td>(4.3)</td>
<td>(0.01)</td>
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<tr>
<td>40ºC</td>
<td>25</td>
<td>48.4</td>
<td>13.2</td>
<td>3.45</td>
</tr>
<tr>
<td>30% n=5</td>
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<td>(6.1)</td>
<td>(0.06)</td>
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</tr>
<tr>
<td>30ºC</td>
<td>19</td>
<td>54.3</td>
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</tr>
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<td>30% n=5</td>
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<td>24ºC</td>
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<td>56.0</td>
<td>14.0</td>
<td>3.46</td>
</tr>
<tr>
<td>30% n=5</td>
<td>(12.7)</td>
<td>(4.1)</td>
<td>(0.05)</td>
<td></td>
</tr>
</tbody>
</table>

Ta: ambient temperature; RH: relative humidity; C<sub>p</sub>: specific heat of the human body. Values given are means and standard deviation (in parentheses).
Estimating changes in mean body temperature

Table 3. Mean Experimental Group (EG) values for change in rectal and mean skin temperature, change in mean body temperature using the traditional two-compartment thermometry model ($\Delta T_{b\_trad}$) using standard core/shell weightings, change in mean body temperature measured using calorimetry ($\Delta T_{b\_cal}$), and the estimation error ($X_0 = \Delta T_{b\_cal} - \Delta T_{b\_trad}$) between thermometry and calorimetry.

<table>
<thead>
<tr>
<th>Oxford Index (°C)</th>
<th>Time (min)</th>
<th>Core</th>
<th>Shell</th>
<th>$T_{re}$= 0.66</th>
<th>$T_{re}$= 0.79</th>
<th>$T_{re}$= 0.90</th>
<th>$T_{re}$= 0.66</th>
<th>$T_{re}$= 0.79</th>
<th>$T_{re}$= 0.90</th>
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</thead>
<tbody>
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<td>29</td>
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<td>+0.42</td>
<td>+0.91</td>
<td>+0.59</td>
<td>+0.53</td>
<td>+0.47</td>
<td>+1.15</td>
<td>+0.57</td>
<td>+0.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.15)</td>
<td>(0.15)</td>
<td>(0.13)</td>
<td>(0.14)</td>
<td>(0.14)</td>
<td>(0.27)</td>
<td>(0.18)</td>
<td>(0.17)</td>
</tr>
<tr>
<td></td>
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<td>+0.74</td>
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<tr>
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<td>(0.24)</td>
<td>(0.49)</td>
<td>(0.35)</td>
<td>(0.35)</td>
</tr>
<tr>
<td></td>
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<td>+0.90</td>
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<td></td>
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<td>(0.25)</td>
<td>(0.28)</td>
<td>(0.29)</td>
<td>(0.31)</td>
<td>(0.68)</td>
<td>(0.55)</td>
<td>(0.53)</td>
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<td>+0.61</td>
<td>+0.56</td>
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<td>+0.54</td>
<td>+1.02</td>
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<td>+0.47</td>
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<tr>
<td></td>
<td></td>
<td>(0.14)</td>
<td>(0.18)</td>
<td>(0.14)</td>
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<td>(0.14)</td>
<td>(0.24)</td>
<td>(0.14)</td>
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<td></td>
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<td>+0.99</td>
<td>+1.00</td>
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<td>+0.68</td>
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<tr>
<td></td>
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<td>(0.34)</td>
<td>(0.33)</td>
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<td>(0.61)</td>
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<tr>
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<td>+1.17</td>
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<td>(0.47)</td>
<td>(0.48)</td>
<td>(0.48)</td>
<td>(0.68)</td>
<td>(0.38)</td>
<td>(0.39)</td>
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<td>+0.55</td>
<td>+0.52</td>
<td>+0.50</td>
<td>+0.90</td>
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<td>(0.44)</td>
<td>(0.27)</td>
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<td>(0.25)</td>
<td>(0.39)</td>
<td>(0.18)</td>
<td>(0.17)</td>
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<td>(0.57)</td>
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<td>(0.32)</td>
<td>(0.52)</td>
<td>(0.25)</td>
<td>(0.24)</td>
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<td>+0.76</td>
<td>+1.24</td>
<td>+0.54</td>
<td>+0.51</td>
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<tr>
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<td>(0.32)</td>
<td>(0.52)</td>
<td>(0.35)</td>
<td>(0.33)</td>
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<td>30</td>
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<td>+0.77</td>
<td>+0.66</td>
<td>+0.57</td>
<td>+1.02</td>
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<td>(0.19)</td>
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<td>+0.80</td>
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<td>+0.21</td>
<td>+0.32</td>
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<td></td>
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<td>(0.41)</td>
<td>(0.23)</td>
<td>(0.22)</td>
<td>(0.23)</td>
<td>(0.27)</td>
<td>(0.16)</td>
<td>(0.13)</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>+0.74</td>
<td>+1.42</td>
<td>+0.97</td>
<td>+0.88</td>
<td>+0.81</td>
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<td>+0.27</td>
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<tr>
<td></td>
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<td>(0.49)</td>
<td>(0.29)</td>
<td>(0.30)</td>
<td>(0.32)</td>
<td>(0.28)</td>
<td>(0.20)</td>
<td>(0.21)</td>
</tr>
</tbody>
</table>

Data for n=9 at 29°C, 25°C, 19°C and 15°C after 30, 60 and 90-min. All values are means and standard deviation (in parentheses). Core temperature measured in rectum ($T_{re}$).

Mean Skin temperature ($\bar{T}_{sk}$) measured as a weighted mean of 12 sites (12). All values are in ºC.
Estimating changes in mean body temperature

Table 4. Results from step-wise regression analyses of estimation error (X₀) with environmental and personal parameters.

<table>
<thead>
<tr>
<th>Variable</th>
<th>30-min</th>
<th>60-min</th>
<th>90-min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>β</td>
<td>P</td>
<td>β</td>
</tr>
<tr>
<td><strong>Final Models</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Tₑ= 0.66)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Constant)</td>
<td>0.642</td>
<td>0.037</td>
<td>0.612</td>
</tr>
<tr>
<td>Heat production</td>
<td>0.017</td>
<td>0.003</td>
<td>0.035</td>
</tr>
<tr>
<td>Body surface area</td>
<td>-0.697</td>
<td>0.002</td>
<td>-0.994</td>
</tr>
<tr>
<td>Env conditions</td>
<td>0.019</td>
<td>&lt;0.001</td>
<td>0.040</td>
</tr>
<tr>
<td>Adjusted R²</td>
<td>0.50</td>
<td></td>
<td>0.54</td>
</tr>
</tbody>
</table>

| **Final Models**  |        |        |        |
| (Tₑ= 0.79)        |        |        |        |
| (Constant)        | 0.572  | 0.065  | 0.477  | 0.359  | 0.618  | 0.389  |
| Heat production   | 0.018  | 0.003  | 0.036  | 0.001  | 0.039  | 0.006  |
| Body surface area | -0.504 | 0.008  | -0.884 | 0.007  | -1.050 | 0.018  |
| Env conditions    | 0.017  | 0.001  | 0.037  | <0.001 | 0.047  | <0.001 |
| Adjusted R²       | 0.42   |        | 0.53   |        | 0.45   |        |

| **Final Models**  |        |        |        |
| (Tₑ= 0.90)        |        |        |        |
| (Constant)        | 0.530  | 0.115  | 0.355  | 0.409  | 0.574  | 0.421  |
| Heat production   | 0.014  | 0.033  | 0.037  | 0.001  | 0.041  | 0.004  |
| Body surface area | -0.434 | 0.016  | -0.791 | 0.016  | -1.017 | 0.021  |
| Env conditions    | 0.014  | 0.007  | 0.035  | <0.001 | 0.044  | <0.001 |
| Adjusted R²       | 0.32   |        | 0.50   |        | 0.44   |        |

Final results from backward regression analyses for: Estimation error (X₀ in ºC) = β₀ + β₁ [Metabolic heat production (in kJ/min)] + β₂ [Body surface area (in m²)] + β₃ [Environmental Conditions (in Oxford index ºC)] + β₄ [Body fat percentage (in % of total body mass)] + β₅ [Body surface area-to-mass ratio (in m²/kg)]. *Note: In all circumstances, body fat percentage and body surface area-to-mass ratio were excluded by the model since they did not correlate significantly with the residual variance in X₀.
Figure Legends

Figure 1. The changes in mean body temperature using the traditional 2-compartment thermometry model (open circles) and the adjusted thermometry model incorporating the predicted correction factor (shaded circles) relative to values directly measured using calorimetry for each individual in the validation group (VG) after 30-min of exercise using a core/shell weighting of 0.66/0.34, 0.79/0.21 and 0.90/0.10. Dashed line indicates line of identity (y = x).

Figure 2. The changes in mean body temperature using the traditional 2-compartment thermometry model (open circles) and the adjusted thermometry model incorporating the predicted correction factor (shaded circles) relative to values directly measured using calorimetry for each individual in the validation group (VG) after 60-min of exercise using a core/shell weighting of 0.66/0.34, 0.79/0.21 and 0.90/0.10. Dashed line indicates line of identity (y = x).

Figure 3. The changes in mean body temperature using the traditional 2-compartment thermometry model (open circles) and the adjusted thermometry model incorporating the predicted correction factor (shaded circles) relative to values directly measured using calorimetry for each individual in the validation group (VG) after 90-min of exercise using a core/shell weighting of 0.66/0.34, 0.79/0.21 and 0.90/0.10. Dashed line indicates line of identity (y = x).

Figure 4. Mean percentage error for changes in mean body temperature estimated using the traditional 2-compartment thermometry model (open circles) and the adjusted thermometry model incorporating the predicted correction factor (shaded circles) relative to values directly measured using calorimetry in the validation group (VG) after 30, 60 and 90-min of exercise using a core/shell weighting of 0.66/0.34, 0.79/0.21 and 0.90/0.10. Error bars indicate 95% confidence intervals.
The graphs show the thermometry relative to calorimetry for different time points, with the following temperatures:

- For the first graph: $T_r/T_s: 0.66/0.34$
- For the second graph: $T_r/T_s: 0.79/0.21$
- For the third graph: $T_r/T_s: 0.90/0.10$

The graphs are plotted over time (min) from 0 to 120 minutes, with the y-axis representing the percentage deviation from the calorimetry readings.