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ORIGINAL ARTICLE

Thermometry and calorimetry assessment of sweat response during exercise in the heat

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Abstract Our objective was to characterise sweat rate responses in a hot environment during rest and subsequent increasing levels of exercise in relation to thermometrically (i.e., rectal, tympanic, mean skin and mean body temperatures) and calorimetrically derived (i.e., change in body heat storage) thermal parameters. Ten healthy males volunteered and entered an environmental chamber set at 42°C. Participants rested seated during their first hour inside the chamber. Thereafter, they exercised to volitional exhaustion on a cycle ergometer at 20 W with step increments of 20 W h^{-1}. Across time, fluctuations in sweat rate were systematically associated with similar fluctuations in the integral of body heat storage ($t = 13.16$, $P < 0.001$), but not rectal ($t = 0.98$, $P > 0.05$), tympanic ($t = 0.81$, $P > 0.05$), mean skin ($t = 0.12$, $P > 0.05$), or mean body ($t = 0.93$, $P > 0.05$) temperatures. In addition, 95% limits of agreement and regression analyses showed that the changes in sweat rate demonstrated the highest agreement and strongest associations with changes in the integral of body heat storage. It is concluded that in a hot environment during rest and subsequent increasing levels of exercise sweat rate is associated with the cumulative changes in the rate of body heat storage.

Keywords Heat loss · Heat storage · Rectal temperature · Mean body temperature · Cycling · Evaporation

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Introduction

Physically active humans in hot environments are capable of generating remarkable amounts of sweat in order to maintain thermal homeostasis (Shibasaki et al. 2006). The control of sweating is influenced by many factors of thermal (e.g., shell and core temperatures) and nonthermal (e.g., mechanoreceptors and baroreceptors) origin (Shibasaki et al. 2006). The interplay of these factors has not been entirely elucidated, yet it is generally believed that eccrine sweat gland secretion is regulated around a threshold of either an internal temperature or an integrated composite of internal and superficial temperatures most commonly considered in the form of a mean body temperature (Yoshida et al. 1995; Shibasaki et al. 2006). As such, mean body temperature is commonly used when expressing and/or evaluating sweating responses during exercise and/or heat exposure (Yoshida et al. 1995; Shibasaki et al. 2006). However, recent evidence has shown that the thermometrically derived mean body temperature is a technique that is inherently limited in its ability to accurately reflect the magnitude of residual body heat storage (Jay et al. 2007). This is noteworthy because it may lead to erroneous conclusions with regards to the control of sweat secretion. The probability of this scenario can be examined by investigating sweat rate responses during simultaneous minute-by-minute measurements of the individual heat balance components by whole-body partitional calorimetry

(Vallerand et al. 1992a, b; Flouris and Cheung 2009). Hence, our objective in this experiment was to characterise sweat rate responses in a hot environment during rest and subsequent increasing levels of exercise in relation to thermometrically (i.e., rectal, tympanic, mean skin and mean body temperatures) and calorimetrically derived (i.e., change in body heat storage) thermal parameters.

Methods

Participants and screening

The experimental protocol conformed to the standards set by the Declaration of Helsinki and was approved by the appropriate ethical review board at Dalhousie University. Ten healthy, physically active, non-smoking males [age 27.3 (8.8) years; height: 1.8 (0.1) m; weight: 77.0 (12.2) kg; body fat: 11.1 (5.9) %; body surface area: 1.9 (0.2) m^2] volunteered. Participants underwent medical screening from an expert cardiologist, which included extensive medical history, a 12-lead ECG as well as cardiac examination. Written informed consent was obtained from all participants after full explanation of the procedures involved.

Experimental protocol

Participants were required to visit the laboratory at approximately 10 a.m. after abstaining from alcohol and heavy exercise for 24 h and caffeine on the testing day. Participants were also advised to avoid excessive stressors such as exposure to extreme hot or cold temperatures for 48 h prior to data collection and particularly during the period between awakening and experimentation and during transit from home to the laboratory.

Participants were instructed to consume 500 mL of water 2 h prior to testing. To ensure appropriate hydration levels, upon arrival and before any testing had begun, urine void (80 mL) was collected in polyethylene specimen jars (Fisher Scientific, Pittsburgh) for the determination of urine specific gravity using a refractometer (Atago, Tokyo, Japan). Euhydration was defined as urine specific gravity <1.02 according to internationally accepted standards (Kavouras 2002). All participants achieved euhydration, and no experimental sessions required rescheduling.

Testing preparation included outfitting the participants with rectal and tympanic temperature thermistors, humidity sensors, and with cotton T-shirt, shorts, track pants, and shirt. Thereafter they entered an environmentally controlled chamber set at ambient temperature and relative humidity equal to 42°C and 30%, respectively (air velocity 0.05 m s^{-1}). During their time inside the chamber, they breathed through a mask while watching a movie or reading. During their first hour inside the chamber, participants were resting seated in a comfortable chair. Thereafter, they exercised to volitional exhaustion on a bicycle ergometer (CycleOps Pro 300PT, Saris Cycling Group, Madison WI, USA) at an initial workload of 20 W, with increments of 20 W h^{-1}. During the thermal protocol, rectal, tympanic, and mean skin temperature, heat production and loss were continuously measured.

Instrumentation

Prior to data collection, participants self-inserted a flexible thermistor probe (Mon-A-Therm Core, Mallinkrodt Medical, St. Louis, USA) to a depth of 15 cm beyond the anal sphincter for the assessment of rectal temperature. A flexible thermistor (MA-100, Thermometrics, Edison, NJ, USA) was inserted in the participants' ear canal and was used as an index of tympanic temperature using a previously described procedure (Flouris and Cheung 2009). Values for rectal and tympanic temperature were recorded throughout the thermal protocol at 8-s intervals using a data logger (Smartreader 8 Plus, ACR, Vancouver, Canada) interfaced with a computer to allow for their continuous monitoring by the investigators. Thereafter, these values were used to provide 1-min mean values for each parameter.

All participants wore the same clothing during the thermal protocol which consisted of commercially available 100% cotton underwear, socks, T-shirt, shorts, track pants and long-sleeve shirt (0.73 clo) covering the entire body except the head and the hands.

The rate of body heat storage ($\dot{S}$) was calculated as:

$$\dot{S} = \dot{M} - \dot{W} - \dot{E}_{res} - \dot{C}_{res} - \dot{E}_{sk} - (\dot{K} \pm \dot{C} \pm \dot{R})$$

where all variables are measured in watts (W) and $\dot{M}$ is the metabolic rate, $\dot{W}$ is the rate of work, $\dot{E}_{res}$ and $\dot{C}_{res}$ are the rates of evaporative and dry (convective) heat flow through the respiratory tract, $\dot{E}_{sk}$ is the evaporative heat flow from the skin, whereas $\dot{K}, \dot{C}$, and $\dot{R}$ represent the conductive, convective, and radiative heat flows from the skin.

The metabolic rate was assessed via open circuit spirometry using an automated gas analyser indirect calorimetry system (TrueOne® 2400, Parvo Medics, Sandy, UT, USA). Breath-by-breath respiratory parameters were recorded and were expressed in 15-s averages while participants inspired room air through a mask. The gas analyser was calibrated with standard gases prior to testing. The metabolic rate was determined using a validated formula (Gagge and Nishi 1983):

$$\dot{M}[(0.23 \cdot \mathrm{RQ} + 0.77) \cdot 21.14] \cdot (60 \cdot \dot{V}O_2) \cdot \mathrm{AD}$$

where (0.23 RQ + 0.77) 21.14 represents the energy equivalent of oxygen consumed (in kJ L^{-1}), RQ is the respiratory quotient, $\dot{V}O_2$ is the oxygen uptake (expressed in L min^{-1} in standard temperature and pressure, dry), and AD is the body surface area (DuBois and DuBois 1916).

The work rate was equal to 0 W for the first hour of testing as participants were resting, with increments of 20 W per hour thereafter. Based on validated procedures (Fanger 1970), the rates of evaporative and dry (convective) heat flow through the respiratory tract were calculated using metabolic rate while assuming an average temperature of around 42°C and corresponding saturated vapour pressure of around 6.51 kPa in the upper respiratory tract.

The estimation of evaporative heat flow from the skin was based on a previously developed model (Cain and McLellan 1998) validated during exercise in the heat (McLellan et al. 1996) and used vapour pressure readings obtained by six pen-shaped humidity probes positioned at three different locations on the body. Each humidity probe (Vaisala HMP50, Helsinki, Finland) incorporated a humidity sensor inside an aluminium body, protected by a membrane filter and plastic grid, leaving a 1-mm air space between the humidity sensor and the probe's protective aluminium body. The pen-shaped probes were attached perpendicular to vapour flow incorporating a total axial aspect width of 12 mm (10 mm humidity sensor and 1 mm protective aluminium body around). Two humidity probes were placed on the upper back, two probes were placed on the abdomen, and two probes were placed on the upper thigh. For each pair of probes, one was attached on the skin (sensor 1 mm above the skin surface) and the other probe was attached at exactly the same position on top of the T-shirt, shorts, or pants (sensor 14 mm above the skin surface). The model was viewed as one-dimensional flow of water vapour through the clothing, which produced resistance to the flow. The water vapour pressure at the skin was predicted from the water vapour measurements provided by the sensors in the clothing. This was, in turn, used in calculating evaporative heat flow from the skin as previously shown (Cain and McLellan 1998), with values recorded and displayed throughout the thermal protocol at 1.5-s intervals using data acquisition software (EasyDaq, Dorset, UK). Thereafter, these values were used to provide 1-min mean evaporative skin heat flow values.

Calculation of mean skin temperature as well as conductive, convective, and radiative heat flows from the skin was achieved using 12 calibrated heat flux transducers with embedded thermistors (FR-025-TH44033-F6, Concept Engineering, Old Saybrook, CT, USA) which were attached to the skin according to a widely-used skin temperature model (Hardy and DuBois 1938) with mean skin temperature and heat flux (including the head) calculated as: 0.07 forehead + 0.14 arm + 0.05 hand + 0.07 foot + 0.13 (shin + calf)/2 + 0.19 (quadriceps + hamstrings)/2 + 0.35 (chest + abdomen + upper back + lower back)/4. Values for temperature and heat flow were recorded and displayed throughout the thermal protocol at 1.5-s intervals using data acquisition software (EasyDaq, Dorset, UK). Thereafter, these values were used to provide 1-min mean values for each parameter.

As typical 'core' to 'shell' ratios for the calculation of mean body temperature range from 2:1 to 3:1 in cold environments (Flouris et al. 2007; Flouris and Cheung 2008) and from 4:1 to 9:1 in hot environments (Stolwijk and Hardy 1977), a 6:1 ratio was used in the present experiment [i.e., body temperature = 0.86 (rectal temperature) + 0.14 (mean skin temperature)].

Sweat rate was measured using a 5.0-cm^2 ventilated capsule placed over the medial inferior aspect of the trapezius muscle. Anhydrous compressed air was passed through the capsule and over the skin surface (Brooks 5850, mass flow controller, Emerson electric, Hetfield, PA, USA). The vapour density of the effluent air was calculated from the relative humidity and temperature measured using the Omega HX93 humidity and temperature sensor (Omega Engineering, Stanford, CT, USA). Sweat rate was defined as the product of the difference in water content between effluent and influent air and the flow rate. The flow rate through the capsule was 1.13 L min^{-1}. The sweat rate value was adjusted for skin surface area under the capsule (expressed in mg min^{-1} cm^{-2}).

Statistical analyses

Given that the kinetics of sweat rate and $\dot{S}$ across time (see "Results" section) alluded to the notion that sweat rate is proportional to the integral of $\dot{S}$ ($\dot{S}_{INT}$), appropriate calculations and analyses were conducted to examine whether this was, in fact, true. The $\dot{S}_{INT}$ was calculated and a best-fit linear regression factor was applied to it (see "Results") in order to lower its values (without changing its distribution or kinetics across time) and bring them closer to the range of sweat rate for comparison purposes.

In the first part of data analysis, Auto-Regressive Integrative Moving Average (ARIMA) was employed given the time series nature of the data. This is because common techniques are limited by the lack of independence amongst sequential data points within a time series. This limitation does not influence ARIMA that can mathematically describe the association between two variables across time and has been successfully employed in the past (Flouris et al. 2008) to identify associations between variables in thermal physiology. Based on the appropriate ARIMA procedure (Box and Jenkins 1976), the sweat rate time series was plotted separately against rectal, tympanic, mean skin and mean body temperature, and $\dot{S}_{INT}$ time series in order to examine for systematic patterns and periodicity (i.e., recurring patterns in repetitive intervals). To statistically address the possibility that two time series (i.e., sweat rate and either rectal, tympanic, mean skin or mean body temperature, or $\dot{S}_{INT}$) were not inherently unpredictable (random-walk model or white noise), the autocorrelation of the residuals from exponential smoothing was calculated for each for a maximum of 15 lags (equivalent to 15 min). Subsequently, ARIMA was used to investigate whether changes in sweat rate time series (dependent variable) were associated with changes in rectal, tympanic, mean skin, mean body temperature, or $\dot{S}_{INT}$ time series (independent variables).

In the second part of data analysis, the changes from baseline in sweat rate ($_{B}$SR), mean body temperature ($_{B}T_{b}$), and $\dot{S}_{INT}$ ($_{B}\dot{S}_{INT}$) were calculated (e.g., sweat rate at time 1 minus sweat rate at time 0) showing the degree of change in mean body temperature and $\dot{S}_{INT}$ for every change in sweat rate. Thereafter, a hierarchical regression analysis (i.e., regression analysis where independent variables are inserted in a pre-specified sequence to observe changes in regression coefficients amongst models) was calculated to predict $_{B}$SR (dependent variable) from $_{B}T_{b}$ and $_{B}\dot{S}_{INT}$ (independent variables). Moreover, the 95% limits of agreement and the percent coefficient of variation (Bland and Altman 1986; Flouris et al. 2005) were calculated to examine the agreement between $_{B}$SR and either $_{B}T_{b}$ or $_{B}\dot{S}_{INT}$. Statistical analyses were performed with SPSS (version 14.0.1, SPSS Inc., Chicago, IL, USA) statistical software package. The level of statistical significance was set at $P < 0.05$.

Results

Given that exercise was performed to volitional exhaustion and not all participants finished at the same time, data were analysed only for minutes that all 10 participants sustained the required work rate. As illustrated in Figs. 1 and 2, the kinetics of sweat rate, heat production and heat loss across time allude to the notion that sweat rate is proportional to the integral of $\dot{S}$ [$\dot{S}_{INT}$ (i.e., the cumulative difference between heat production and loss)]. Thus, $\dot{S}_{INT}$ was calculated as:

$$\dot{S}_{INT} = (\text{integral of heat production} - \text{integral of heat loss})/13595.55 + 36.54$$

The second part of the formula represents a best-fit linear regression factor which was applied to $\dot{S}_{INT}$ in order to lower its values (without changing its distribution or kinetics across time) and bring them closer to the range of sweat rate for comparison purposes.

Figure 1 illustrates mean heat production and loss across time, while Fig. 2 illustrates mean results for rectal, tympanic, mean skin and mean body temperature, as well as sweat rate and $\dot{S}_{INT}$ across time. It was evident that heat loss followed the changes in heat production, albeit with some delay. Sweat rate increased steadily from the 50th to the 150th minute of exposure where it reached a plateau. In a similar fashion, $\dot{S}_{INT}$ increased steadily from the 60th to the 160th minute of exposure, reaching a plateau thereafter. Rectal and mean body temperatures increased linearly with time similarly to tympanic temperature which, however, showed some delay. During the initial phase of the experiment mean skin temperature increased reaching a plateau at 80 min.

The first part of statistical analysis examined the validity of the aforementioned observations using five ARIMA models. This is because heat exposure and exercise in the present experiment represented disturbances (shocks) that somehow affected the level of a series (in this case sweat rate) as well as the level of another series (in this case rectal, tympanic, mean skin or mean body temperature, or

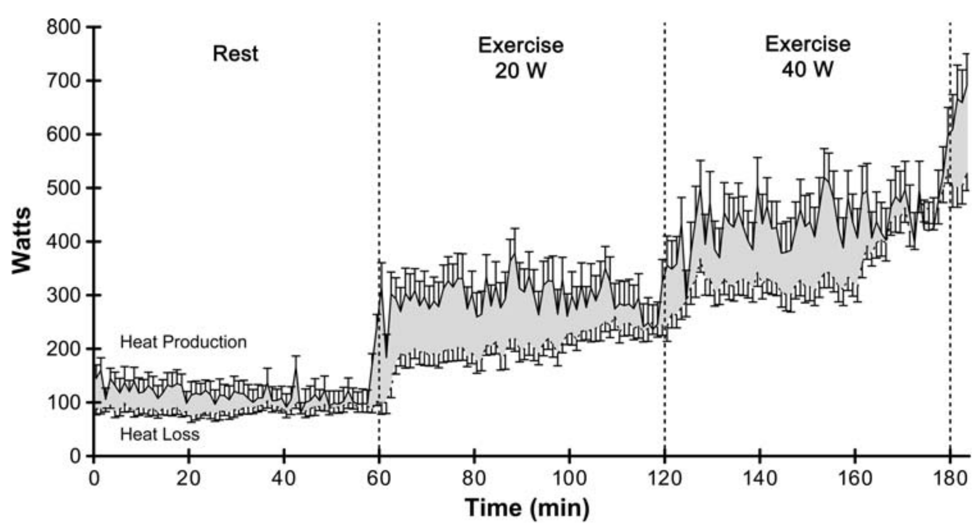

Fig. 1 Mean (SD) whole-body partitional calorimetry data for the rate of net heat production and loss during the thermal protocol. Values are presented only for minutes that all 10 participants sustained the required work rate. The *shaded area* represents the rate of residual body heat storage, while *vertical lines* identify changes in work rate reflecting the protocol timeline

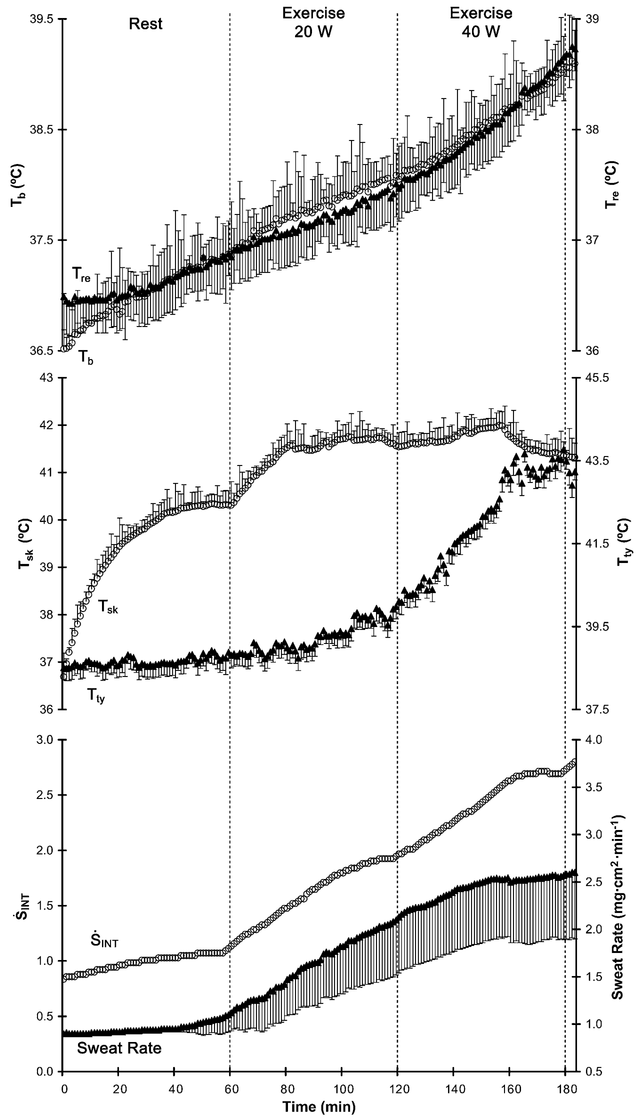

Fig. 2 Mean (SD) values for rectal temperature (T_{re}), mean body temperature (T_b), mean skin temperature (T_{sk}), tympanic temperature (T_{ty}), integral of body heat storage ($\dot{S}_{INT}$) and sweat rate during the thermal protocol. Graph properties are identical to Fig. 1

$\dot{S}_{INT}$). Based on these disturbances, ARIMA can mathematically describe the association between two time series [(e.g., sweat rate and rectal temperature) similar to what regression analysis does for non-time series data]. ARIMA results demonstrated that, across time, fluctuations in sweat rate were systematically associated with similar fluctuations in $\dot{S}_{INT}$ ($t = 13.16$, $P < 0.001$), but not rectal ($t = 0.98$, $P > 0.05$), tympanic ($t = 0.81$, $P > 0.05$), mean skin ($t = 0.12$, $P > 0.05$), or mean body ($t = 0.93$, $P > 0.05$) temperature.

In the second part of data analysis, the hierarchical regression demonstrated that both $_BT_b$ ($P = 0.001$) and $_B\dot{S}_{INT}$ ($P < 0.001$) were associated with $_B$SR (Table 1). Yet, the coefficient of determination (R^2) which demonstrates the amount of variability explained by each model was increased at $P < 0.001$ when $_B\dot{S}_{INT}$ was forced into the second model. The 95% limits of agreement and the percent coefficient of variation for the relationship between $_B$SR and $_BT_b$ were 0.5 ± 0.35 and 17.5%, respectively. The same indices for the relationship between $_B$SR and $_B\dot{S}_{INT}$ were 0.1 ± 0.01 and 7.3%, respectively.

Table 1 Unstandardised regression coefficients (SE) from hierarchical regression analysis predicting changes in sweat rate

DV	R^2	IV: $_B$SR	
$_BT_b$	0.94	0.91 (0.02)	−0.18 (0.06)
$_B\dot{S}_{INT}$	0.98		1.20 (0.06)
Constant		−0.37 (0.03)	0.01 (0.02)

ANOVA for both models was statistically significant at $P < 0.001$. Both dependent variables were statistically significant predictors ($P < 0.05$). R^2 change was significant at $P < 0.001$

DV dependent variables, R^2 coefficient of determination for each model, *IV* independent variable, $_B$SR, $_BT_b$, and $_B\dot{S}_{INT}$ change from baseline in sweat rate, mean body temperature and interval of body heat storage rate (e.g., sweat rate at time 1 minus sweat rate at time 0)

Discussion

Partitional calorimetry data demonstrated that the current experimental protocol was successful in creating distinctively increasing levels of heat production. In response to the adopted protocol, it was evident that heat loss adapted appropriately to changes in heat production, albeit with a brief delay. Sweat rate and $\dot{S}_{INT}$ remained relatively unchanged until about 1 h into the exposure, and increased steadily thereafter reaching a plateau towards the end of the protocol. Rectal and mean body temperatures increased linearly with time and so did tympanic temperature, albeit with a 100-min delay. This delay of tympanic temperature may be attributed to the exercise which was limited to the lower body. Mean skin temperature showed an initial increase followed by a plateau at the second half of the experiment. The validity of these observations was confirmed in the first part of data analysis through ARIMA which showed that across time, fluctuations in sweat rate were systematically followed by similar fluctuations in $\dot{S}_{INT}$, but not rectal, tympanic, mean skin or mean body temperatures. The second part of data analysis supported these findings showing that changes in sweat rate correspond to a certain degree with changes in mean body temperature, but demonstrate the highest agreement and are more closely linked with changes in $\dot{S}_{INT}$.

Previous research has proposed that eccrine sweat gland secretion is regulated around a threshold of either internal temperature or mean body temperature (Yoshida et al.

1995; Shibasaki et al. 2006). However, these sweating thresholds were investigated through thermometry, a technique that was recently found to be inherently limited in its ability to accurately reflect the magnitude of residual $\dot{S}$ (Jay et al. 2007). Through partitional calorimetry measurements, our results show that sweat rate shows a correspondence with mean body temperature, but it is more closely linked to $\dot{S}_{INT}$. In principle, the thermometrically derived mean body temperature should be parallel to $\dot{S}_{INT}$ during our experiment. However, due to the increased thermal inertia of the superficial and, particularly, internal temperature measurements that create mean body temperature, this index is less accurate (Jay et al. 2007) and becomes obsolete when calorimetry data can be retrieved.

A recent calorimetric experiment showed that thermal inertia is reduced when the body is already warm from previous exercise bouts (Kenny et al. 2009). These results mirror earlier findings of a shortened onset of local sweating (Kruk et al. 1990) and skin vasodilation (Kenny et al. 1996) in successive exercise bouts. Our findings combine these lines of evidence demonstrating that sweat rate is associated with $\dot{S}_{INT}$, a surrogate of thermal inertia. Our results, therefore, suggest that the prompt sweat rate increase observed at the onset of dynamic exercise and before a measurable change in internal temperature (Van Beaumont and Bullard 1966) may be attributed to thermal factors. As shown in the present experiment, thermometrically derived indices of core and mean body temperature are inherently limited by an increased thermal inertia and cannot be used to describe abrupt changes in thermal balance.

It is necessary to acknowledge that we measured sweat rate only on the upper back (i.e., medial inferior aspect of the trapezius muscle), yet sweat rate is not uniform across the body surface (Baker et al. 2009). We chose this site given that the ventilated capsule technique requires a wide flat surface to avoid air leakage. As such, the upper back is a site often used when the ventilated capsule technique is adopted (Journeay et al. 2005). Our evaporative heat loss estimates may have been influenced by nonthermal factors, which are known to play a significant role in heat balance (Journeay et al. 2005). Furthermore, as oesophageal temperature is considered a good indicator of blood temperature perfusing the brain (Shiraki et al. 1986), it is tenable that this variable could have shown a relationship with sweat rate. Moreover, regional differences in blood distribution could have affected the time-line response of our temperature readings. Apropos, such blood distribution alterations should have also affected our $\dot{S}_{INT}$ readings in a similar fashion, yet this variable appeared unaffected demonstrating a close link with sweat rate.

In conclusion, the vast majority of germane experiments to date have investigated various sweating thresholds through thermometry, a technique that was recently found to be inherently limited in its ability to accurately reflect the magnitude of residual $\dot{S}$ (Jay et al. 2007). In this paper, we found that in a hot environment during rest and subsequent increasing levels of exercise sweat rate is associated with the cumulative changes in the rate of body heat storage. Pertinent calorimetric experiments investigating the interplay between thermal and nonthermal factors in the control of eccrine sweat gland secretion should be projected in the future.

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Conflict of interest statement There is no financial or other relationship that might be perceived as leading to a conflict of interest in relation to this work.

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