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Estimation of metabolic energy expenditure from core temperature using a human thermoregulatory model

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ABSTRACT

Human metabolic energy expenditure is critical to many scientific disciplines but can only be measured using expensive and/or restrictive equipment. The aim of this work is to determine whether the SCENARIO thermoregulatory model can be adapted to estimate metabolic rate (*M*) from core body temperature (T_C). To validate this method of *M* estimation, data were collected from fifteen test volunteers (age = 23 ± 3 yr, height = 1.73 ± 0.07 m, mass = 68.6 ± 8.7 kg, body fat = 16.7 ± 7.3%; mean ± SD) who wore long sleeved nylon jackets and pants ($I_{tot,clo}$ = 1.22, I_m = 0.41) during treadmill exercise tasks (32 trials; 7.8 ± 0.5 km in 1 h; air temp. = 22 °C, 50% RH, wind speed = 0.35 ms^{-1}). Core body temperatures were recorded by ingested thermometer pill and *M* data were measured via whole room indirect calorimetry. Metabolic rate was estimated for 5 min epochs in a two-step process. First, for a given epoch, a range of *M* values were input to the SCENARIO model and a corresponding range of T_C values were output. Second, the output T_C range value with the lowest absolute error relative to the observed T_C for the given epoch was identified and its corresponding *M* range input was selected as the estimated *M* for that epoch. This process was then repeated for each subsequent remaining epoch. Root mean square error (RMSE), mean absolute error (MAE), and bias between observed and estimated *M* were 186 W, 130 ± 174 W, and 33 ± 183 W, respectively. The RMSE for total energy expenditure by exercise period was 0.30 MJ. These results indicate that the SCENARIO model is useful for estimating *M* from T_C when measurement is otherwise impractical.

1. Introduction

Metabolic energy expenditure rate (*M*) has been described as “the single most important unifying aspect of animal biology” (Halsey et al., 2008; Brown et al., 2004). Specific to humans, measuring M has been suggested as a means of monitoring and reducing obesity (Jeor, 1997), estimating nutritional requirements (Long et al., 1979), maintaining energy balance during athletics (Ekelund et al., 2002), and combatting the negative effects of diabetes (Sigal et al., 2006). Metabolic rate is also an essential input to human thermoregulatory models designed to estimate several physiological parameters including: heat storage, exercise thermal-work strain, metabolic fuel requirements, and water requirements (Kraning and Gonzalez, 1997; U.S. Army Research Institute of Environmental Medicine, 2015; Xu and Werner, 2001; Potter et al., 2017).

Despite its importance and utility, *M* is challenging to measure outside the laboratory. Indirect measurement of M derived from expired O_2 and CO_2 typically requires that the subject wear a face-mask or mouthpiece connected to an often bulky apparatus (e.g., mounted on a rolling cart, backpack, or harness) (Macfarlane, 2001). Measuring *M* by doubly labeled water (Schoeller and Santen, 1982) is both accurate and precise, but costly and limited to mean estimates between two time

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Abbreviations: BM, body mass (kg); T_C, core body temperature (°C); $T_{C,est}$, estimated core body temperature (°C); $T_{C,match}$, matched core body temperature (°C); $T_{C,obs}$, observed core body temperature (°C); $T_{C,range}$, core body temperature range (°C); hr, hour; H, height (m); I_m, vapor permeability index; $I_{tot,clo}$, total insulation including boundary air layers (clo); min, minute; *M*, metabolic rate (W); M_{est}, estimated metabolic rate (W); M_{max}, maximum metabolic rate (W); M_{obs}, observed metabolic rate (W); M_{range}, metabolic rate range (W); M_{rst}, resting metabolic rate (W); MAE, mean absolute error; R, correlation coefficient; RH, relative humidity (%); RMSE, root mean square error; SD, standard deviation; T_A, air temperature (°C); TEE, total energy expenditure (MJ); TEE_{est}, estimated total energy expenditure (MJ); TEE_{obs}, observed total energy expenditure (MJ); TDEE, total daily energy expenditure (MJ); yr, year

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points, generally on the scale of 12–24 h (Schoeller and Santen, 1982; Butler et al., 2004). Accelerometers have been used to estimate *M*, but often require equations and calibrations customized to the type of activity, device placement, device sensitivity, gait, load carried, and incline (Halsey et al., 2008; Chen and Sun, 1997). Metabolic rate during exercise has also been estimated from heart rate but accuracy can be affected by activity type (Strath et al., 2000; Rennie et al., 2001; Vokac et al., 1975; Maas et al., 1989; Scharff-Olson et al., 1992) and may require calibration to the individual to achieve reasonable accuracy.

Metabolic rate is also a key input to the human heat balance equation describing heat exchange between an individual's body and the environment (Gagge and Gonzalez, 2011; Fundamentals, 2013). In this context, *M* is used to calculate an organism's heat production as a byproduct of the transformation of chemical energy during aerobic and anaerobic activities, including shivering (Gagge and Gonzalez, 2011). The heat storage equation and *M* inputs are therefore frequent components of human thermoregulatory models that estimate core body temperature (T_C).

The SCENARIO thermoregulatory model is one such thermoregulatory model which has been validated for the estimation of T_C during physical activity in warm environments using work rate, environmental conditions, and worn ensemble biophysical characteristics as inputs (Kraning and Gonzalez, 1997). Although originally designed and validated for estimating T_C from *M*, the SCENARIO model is also capable of estimating *M* from time series T_C values. Total daily energy expenditure (TDEE) data calculated from *M* estimated by SCENARIO were similar to TDEE values measured using double labeled water during Marine Rifle Squad patrols without specific knowledge of daily activities (Welles et al., 2015).

The present work seeks to extend the previous validation of SCENARIO estimated *M* by comparing estimated *M* on the five minute timescale (versus TDEE). Specifically, *M* values estimated (M_{est}) from observed T_C values ($T_{C,obs}$) were compared to observed indirect calorimeter *M* values (M_{obs}) to determine the model's accuracy at estimating *M*. The accuracy of the SCENARIO model's T_C estimates ($T_{C,est}$) from M_{obs} values were also examined in order to ensure that the model is functioning as intended prior to adaption for *M* estimation.

2. Methods

Each volunteer participated in two to three approximately 23 h monitoring periods in an indirect calorimeter chamber (Hill et al., 1991). Each stay included a treadmill running exercise session lasting 70 min. Exercise sessions were comprised of a 10 min warmup during which volunteers were permitted to stretch and engage in low intensity movements for 4 min followed by a standardized progression over 6 min from a 4.8 km/h walk to an 8.0 km/h jog. Once the warmup was complete, volunteers ran 7.8 ± 0.5 km in an hour or less (mean ± standard deviation (SD)).

Data collected while volunteers were inside the indirect calorimeter chamber included volunteer physiological responses, chamber environmental conditions, and *M*. These data, as well as previously collected volunteer anthropometric characteristics and clothing biophysical characteristics were input to the SCENARIO model to produce estimates of both T_C and *M*. Core temperature and *M* were estimated for the 20 min prior to the exercise session, the 70 min exercise session, and 60 min following exercise for a total of 150 min.

2.1. Volunteers

Twenty one (21) volunteers were recruited for this study after being briefed on the purpose, risks, and benefits of the study and provided written informed consent prior to their participation. All volunteer recruitment and data collections were in accordance to the policies for protection of human volunteers as prescribed in Army Regulation 70-25 and SECNAVINST 3900.39D as well as the provisions of 32 CFR Part 219.

Of the original group of 21, fifteen (15) volunteers were ultimately included in this investigation after six volunteers were dropped due to equipment malfunctions, sensor artifacts, and lapses in compliance. Of the 15 volunteers, 13 completed 2 trials (total: 26 trials) and 2 completed 3 trials (total: 6 trials) for a total of 32 trials with exercise periods. Table 1 summarizes the demographic and anthropometric data of the 15 volunteers including sex, height (H; self-report), age (self-report), body mass (BM; shorts and t-shirt), and percent body fat (skin fold caliper) (Singhal and Siddhu, 2011).

2.2. Clothing Biophysical Characteristics

A clo is a unit of thermal resistance defined as the insulation required to keep a resting human comfortable at 21 °C (ASTM F1291-16, 2016). A clo value of 1 is equal to 0.155 $K\bullet m^2/W$ and roughly equivalent to wearing an ensemble including men's underwear briefs, khaki pants, belt, socks, athletic shoes, and a short-sleeved shirt ($I_{tot,clo}$ = 1.17 clo) (ASTM F1291-16, 2016). The permeability index is a nondimensional index from 0 to 1 where 0 indicates a garment or ensemble is impermeable to vapor transfer and does not allow evaporative vapor/heat transfer. An i_m of 1 indicates the theoretical maximum of evaporative heat loss given the worn ensemble's insulation and the ratio of $i_m/I_{tot,clo}$ indicates the “cooling power” of an ensemble (ASTM F1868-17, 2017).

During the pre-exercise period and exercise sessions, volunteers wore their own running shorts, shirt, and sneakers as well as the U.S. Army Physical Training (PT) uniform consisting of a long sleeved nylon jacket and nylon pants. The total clothing insulation ($I_{tot,clo}$) and water vapor permeability index (i_m) values for the PT uniform were 1.22 and 0.41 respectively and were determined by thermal manikin (ASTM F1291-16, 2016) for use as model inputs accounting for ensemble thermal properties. However, volunteers were permitted to change their clothing after concluding the exercise session (during the 60 post-exercise period). The changes in clothing were not documented and did not necessarily occur at the same elapsed time for all volunteers or trials. Therefore, PT uniform ensemble values were used as inputs for modeling the entirety of the data.

2.3. Environmental conditions

Air temperature (T_A) and relative humidity (RH) for the calorimetry chambers were set to 22 °C T_A and 50% RH soon after the volunteers awoke (> 30 min before the pre-exercise period) and remained at these settings for the duration of the pre-exercise and exercise sessions. This allowed the chamber conditions to stabilize at the desired values before exercise began. The volunteers were free to change these settings the evening prior and after completing the exercise session. After being set, T_A was regulated to maintain relatively constant with fluctuation of less than ± 2 °C. Air volume and composition values were computed, both real time and overall, on a standard temperature and pressure basis. Small fluctuations in barometric pressure (770–750 mmHg) were generally observed over extended periods of time as air masses moved through the research facility's geographical area. Within one 24 h period it is uncommon for pressure to change more than ± 2–4 mmHg. For modeling purposes, air movement was assumed to be 0.35 ms^{-1} based on accepted estimates (Fundamentals, 2013) while observed values for T_A and RH were used as model inputs.

Table 1
Volunteer anthropometric characteristics (mean ± standard deviation).

	Age (yr)	Height (m)	Mass (kg)	Body Fat (%)
Males (n = 11)	22 ± 3	1.74 ± 0.07	70.9 ± 8.3	12.7 ± 1.9
Females (n = 4)	23 ± 4	1.68 ± 0.04	62.5 ± 7.4	26.8 ± 5.7
Combined (n = 15)	23 ± 3	1.73 ± 0.07	68.6 ± 8.7	16.7 ± 7.3