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ORIGINAL ARTICLE

Peter Tikuisis · Michel B. Ducharme

The effect of postural changes on body temperatures and heat balance

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Abstract Early studies have demonstrated that rectal temperature (T_{re}) decreases and mean skin temperature ($\bar{T}_{sk}$) increases in subjects changing their posture from standing to supine, and vice versa. Such changes have important implications insofar as thermal stress experiments are conducted and interpreted. However, the extent of these changes between steady-state conditions is not known. In addition, it is not known whether thermal balance is also affected by postural changes. To examine these questions, 11 healthy males were exposed to a thermoneutral air environment (28.2–28.5°C and 40% relative humidity) in various postures at rest. Body temperatures, heat losses, and metabolic rate were measured. Subjects wore shorts only and began in an upright posture (standing or sitting at an inclination of 7.5°) on a customized tilt-table. They were tilted twice, once into a supine position and then back to the original upright position. Each tilt occurred after steady state was satisfied based on the subject's circadian variation of T_{re} determined previously in a 4.25 h control supine trial. Times to supine steady state following the first tilt were [mean (SE)] 92.6 (6.4) and 116.6 (5.1) min for the standing and sitting trials, respectively. Times to upright steady state following the second tilt were 107.9 (11.4) and 124.1 (9.0) min. Mean steady-state T_{re} and $\bar{T}_{sk}$ were 36.87 (0.07) and 34.04 (0.14), 37.47 (0.09) and 33.48 (0.14), and 37.26 (0.05) and 33.49 (0.10) °C for supine, standing, and sitting, respectively. Thermal balance was attained in all steady-state conditions, and allowing for a decrease in the weighting factor of T_{re} for mean body temperature in the upright postures, it also appears that thermal balance was preserved between changes in posture. These results are consistent with no perceived changes by the subjects in their thermal comfort and skin wetness.

P. Tikuisis (✉) · M.B. Ducharme
Defence and Civil Institute of Environmental Medicine,
1133 Sheppard Avenue West, P.O. Box 2000, North York, Ontario, Canada M3M 3B9

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Introduction

The effect of postural changes on body temperatures (T_b) is occasionally neglected in studies on thermoregulation. Recently, we reported a small, but significant decrease in the rectal temperature (T_{re}) of subjects prior to a cold exposure trial (Tikuisis et al. 1991a). The subjects had undergone preparation in a standing position and subsequently rested comfortably at thermoneutrality in a supine position for 30 min to obtain pre-exposure data. T_{re} decreased significantly during this latter period and it appeared that its eventual steady-state value would be less than 37°C. In another unrelated experiment (Ducharme and Tikuisis 1991), the mean steady-state T_{re} of subjects lying down and subsequently sitting in a thermoneutral environment were 36.97 and 37.33°C, respectively. These results strongly suggest that T_b changes upon postural shifts without any change in the ambient conditions.

Indeed, studies on such changes have been conducted many years ago. Kleitman and Doktorsky (1933) reported a consistent decrease in T_{re} in four males lying down after standing for about 1 h, and vice versa. They attributed these changes to differences in metabolic heat production upon the variation in muscle tonus. A later study by Cranston et al. (1954) confirmed these changes in T_{re} and documented several others, but challenged the supposition that metabolic changes were responsible. In their study, three subjects stood without support until steady state was attained, and then they assumed a supine posture. Following 30–45 min in this position, they resumed the standing posture. The fall in T_{re} in the supine position ranged from 0.25 to 0.63°C, although steady state was not reached. Upon return to the standing position, a gradual increase in T_{re} was noted in all subjects. Their explanation of these changes, supported by others (Amberson 1943; Nielsen et al. 1939; Rowell 1986; Shiraki et al. 1987), suggested that the decrease in venous blood return from the legs due to a reflectively induced cutaneous vasoconstriction (Zoller et al. 1972) reduces the net heat loss from the legs and, hence, the volume of cooled venous blood. Upon lying down, the increase in cutaneous blood supply increases the return of cooled venous blood from the legs resulting in an enhanced core cooling through convective heat exchange (Collins et al. 1982; Mittleman and Mekjavic 1988).

This causal relationship between an orthostatic-mediated change in blood flow distribution and core temperature change was the subject of a very recent investigation by Tanabe and Shido (1994). These investigators applied lower body negative pressure (LBNP) to subjects in a supine position to simulate the orthostatic pressure experienced in a standing position. After a steady-state condition was attained, the LBNP was released to simulate a postural change from standing to supine. While a decrease in T_{re} was measured following the release of LBNP, they did not wait until steady state was attained. If they had, it is very likely that T_{re} would have returned to their pre-release values considering that the pre-release values (36.8–36.9°C) were within the range of values found under normal supine conditions. Hence, although their work demonstrates that blood flow redistribution induced by changes in orthostatic pressure is largely responsible for T_b changes, these values do not necessarily define the magnitude that can be expected from an actual change in posture.

Given the important implications that changes in T_b unaccounted for by postural changes may have on the procedure and interpretation of thermal experiments, a study was designed to measure the changes more precisely and completely (to steady state). In addition to temperature measurements at several body sites, heat loss and metabolic heat production were also measured to ascertain that thermal balance was attained at steady state. Since skin and deep core temperature changes are opposed upon postural changes, it is conceivable that thermal balance is also preserved through compensatory changes in these temperatures. This hypothesis is supported by the observation that subjects in a thermoneutral air environment do not sense a change in their thermal status following changes in posture (Tikuisis et at. 1991a) and will be explored in this study.

Methods

Subjects

Experiments were conducted with 11 non-smoking male volunteer subjects, 23–40 years old. In accordance with Institutional Human Ethics Committee Guidelines for experimentation, each subject was fully informed of the experimental procedure and risks involved before giving his written consent. In addition, subjects were medically screened to insure a normal state of health. Weight and height ranged [mean (SE)] from 70.2 to 103.0 kg [81.0 (2.9)] and 173 to 185 cm [179 (1)].

Procedures

All subjects reported separately to the laboratory on three occasions at the same time each morning and 1 week apart. On the first occasion, a control (CN) trial was conducted where the subject maintained a resting supine position on a tilt-table (TT; described below) for 255 min. These trials were conducted to characterize each subject's circadian rhythm and natural short-term fluctuations in T_{re}. The latter characteristic was used to establish criteria for declaring a steady-state condition, as outlined further below.

The second and third trials began with the subject in an upright position [randomly ordered between standing (ST) and sitting (SI)] until steady state was attained, then tilting the subject to the supine position and maintaining it until steady state was again attained. This was followed by a final tilt back to the original position and waiting until a final steady state was attained. Before arriving on the morning of the experiment, the subject was instructed to abstain from alcohol for 48 h and exercise for 24 h, and was restricted to a light breakfast with no caffeine consumption. During the experiment, the subject was instructed to minimize all movements and did not consume any food or drink, nor require urination. To alleviate boredom, the subject viewed video films and received the audio portion through headphones.

Upon arrival, the subject was instrumented with a rectal probe (self-inserted 15 cm and secured in place with a harness), surface-mounted heat flux transducers (HFT), and surface-mounted electrodes for heart rate monitoring. The rectal probe was a custom-fabricated single unit with three enclosed pre-calibrated thermistors (model 400, Yellow Springs Instruments, Yellow Springs, Ohio) separated 2 cm apart along the probe's length beginning at the tip. This allowed a broader measure of deep T_b. HFTs [model HA13-18-10-P(C), Thermonetics, San Diego, Calif.] were first re-calibrated and corrected for their thermal insulation (Ducharme et al. 1990). They were then placed on 12 locations of the body to obtain mean-weighted heat flux ($\overline{HF}$) and skin temperatures (T_{sk}) according to the placement and weighting factors of Olesen (1984). Three paediatric electrodes (Medi Trace, Graphic Controls Canada, Gananoque, Ontario, Canada) were used to measure heart rate. All values were measured continuously and recorded every minute during the experiment using a data acquisition system (HP-3052A, Hewlett-Packard, San Diego, Calif.).

Metabolic rate (MR) was determined (using the method described in Tikuisis et al. 1991b) from the O_2 and CO_2 analysis of the expired gas (Ametek Thermox Instruments, Pittsburgh, Pa.) and volume ventilation measurements (Alpha Technologies VMM 110, Laguna Hills, Calif.). Expired gas was collected via a mouthpiece continuously for 15 min at the following times: every 30 min until steady state was reached and prior to and immediately following a tilt in posture.

Tilting the subject occurred when the subject reached a steady-state T_{re}. At steady state, small fluctuations in T_{re} can be expected which are unique to each individual These fluctuations were characterized in the CN trials and applied as criteria for tilting in the subsequent tilt trials, as follows. First, the subject's measured T_{re} during the CN trial was divided into 17 segments of 15 min each. If the change in T_{re} was monotonic within a time segment indicating a heating or cooling trend, then those values were ignored for the establishment of the criteria. Where fluctuations occurred within each time segment (i.e., no monotonic trend), the maximum difference (magnitude only) in T_{re} values were averaged over all acceptable time segments to obtain the mean (SD) of the fluctuations. Two personal criteria (PC) values were arbitrarily determined from these

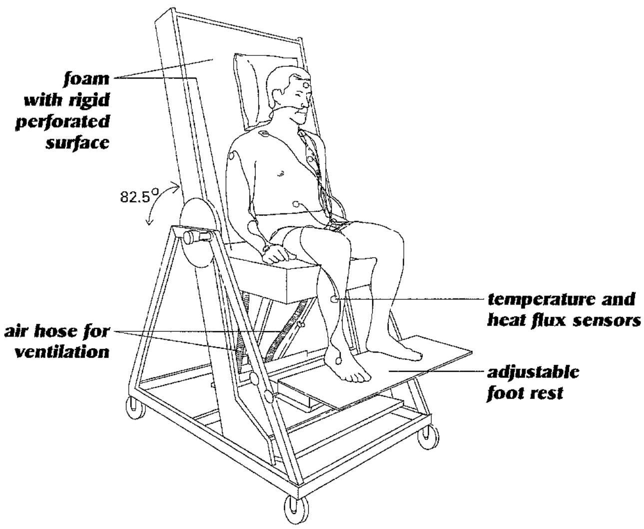

Fig. 1 Schematic of the tilt-table shown in its sitting configuration

values for each subject: PC_1 = mean + SD, and PC_2 = mean + 2·SD. During the second and third trials (involving tilts) when T_{re} fluctuated and the maximum difference within a 15-min period did not exceed PC_1, the subject was considered to have entered a steady state During the next 15 min, MR was measured and the subject's T_{re} was checked to ensure that the PC_1 criterion was still satisfied. In addition, over the combined 30-min period, if the maximum difference in T_{re} did not exceed PC_2, then the subject was declared to be in a steady state. Once these criteria were satisfied, the subject was tilted. It should be noted that these criteria do not imply a constant T_{re} at steady state or exclude long-term trends; as will be seen during the CN trials, T_{re} tended to rise in response to the circadian rhythm superimposed with minor fluctuations in T_{re}.

A TT was designed exclusively for the experiment (see Fig. 1). The major requirement was that once the subject was positioned on the TT, he was to remain on it throughout the trial with minimal exertion on his part. Thus, the TT was constructed with a folding section that formed a seat when pulled out; in this case, the subject, while lying down, was instructed to lift his legs and bend his knees into a sitting configuration while the seated section was folded out. Once locked into position, the TT was then rotated to a near vertical position and the subject assumed a sitting position A foot rest was adjusted to maintain a natural and comfortable position. When rotating back to supine, the procedure was reversed, and changes from supine to standing only required rotating the TT. In the upright positions (sitting and standing), the TT was offset 7.5° from vertical (see Fig. 1) to eliminate any effort on the subject to maintain balance, thus keeping his metabolic rate to a minimum. All tilts were performed within a few seconds.

Other requirements of the TT were to maintain the subject sufficiently comfortable to minimize voluntary movements and to maximize his contact with the ambient conditions over a period of several hours. Thus, a bed of foam (10 cm thick) was constructed and layered with spacing material (1.5 cm) through which room air was pumped and allowed to percolate imperceptibly across the contact area of the subject's skin. This was intended not only to maximize exposure to the ambient condition, but also to prevent heat and moisture build-up which could otherwise alter the desired thermoneutral condition. This construction also optimized comfort by avoiding contact points that could provoke unwanted movement.

During all trials, the subject was asked to rate his thermal sensation every 15 min. Since the trials were conducted within a thermoneutral zone [28.2–28.5°C and 40% relative humidity; (Fanger 1970)], a thermal sensation scale was designed to be especially sensitive to small changes. It involved two ratings, one on thermal comfort (TC) and the other on skin wetness (SW). TC was rated from 0 to 10 (0 = chilled, 1 = cool, 3 = slightly cool, 5 = comfortable, 7 = slightly warm, 9 = warm, and 10 = flushed). The subject was instructed to choose intermediate values if necessary. SW was rated for five sites (underarm, forehead, chest, back, and hand) from 0 to 2 (0 = dry, 1 = damp, 2 = wet) and the subject could interpolate with half values if necessary

Calculations and statistical analysis

Mean body temperature ($\bar{T}_b$) in the supine position was based on the coefficients given by Hardy and DuBois (1938) as follows

$$\bar{T}_b = 0.8\ T_{re} + 0.2\ \bar{T}_{sk} \quad (1)$$

where T_{re} was determined by a simple average of the three sites of the multi-thermistor rectal probe and $\bar{T}_{sk}$ is the mean-weighted skin temperature based on the weighting factors ascertained by Olesen (1984) of the 12 skin sites measured. $\overline{HF}$ was determined using the same weighting factors. However, in a follow-up study where it was possible to replicate the experimental apparatus in a human calorimeter (Snellen, Memorial University, St. John's, Newfoundland, Canada), it was found that $\overline{HF}$ overestimated the overall dry heat loss by 18.9%. This level of overestimation is consistent with values obtained from other mean-weighted approximations involving from 4 to 12 measured sites (tabled in Olesen 1984). It is noteworthy that the Olesen (1984) weighting factors were calibrated against the measurements of 14 evenly weighted skin sites distributed over the body to represent equal surface areas. The values reported herein have been corrected according to the calorimetric test. Where regional values of $\bar{T}_{sk}$ are reported (e.g., trunk, upper arm, upper leg, and lower leg), the relative contribution of the individual sites were normalized according to the Olesen (1984) weighting factors. The trunk value comprises the left upper chest and right scapula, the upper arm comprises the upper section of the right arm and the lower section of the left upper arm, the upper leg comprises the anterior right and posterior left thighs, and the lower leg comprises the right shin and left calf of the legs.

The rate of change in body heat content (heat storage, S) was determined by indirect calorimetry using:

$$S = \text{MR} - \overline{\text{HF}} - E_{sk} - E_r - C_r \quad (2)$$

where E_{sk} is the latent (evaporative) heat loss from the skin, E_r is the latent respiratory heat loss, and C_r is the dry respiratory heat loss. These variables and MR were calculated according to the procedure outlined in Tikuisis et al. (1991b) with one exception; the temperature of the expired air (used in the calculation of respiratory heat loss) was estimated herein using the regression equation of McCutchan and Taylor (1951). The calculation of evaporative and respiratory heat losses was validated in separate trials with weight changes and direct calorimetry (follow-up study cited above). These losses are small in comparison to $\overline{HF}$, hence where applicable, the sum of E_{sk}, E_r, and C_r will simply be reported as $E + R$.

Since the time of tilting was dependent on the subject reaching a steady-state T_{re}, these times naturally varied between subjects. To obtain meaningful averages of the responses, segments of the data (identified as DS) were extracted from the record and arranged as follows. For the CN trials, DS1 through DS6 refer to consecutive 30 min periods during the last 3 h of exposure (to examine any long-term trends in the supine position). For the ST and SI trials, DS1 refers to the entire last 3 h of the CN trials [to provide an overall average control value (Supine-C) for comparison]. DS2 and DS4 refer to the 30-min steady-state periods immediately preceeding the first (from upright to supine) and the second (from supine to upright) tilts, respectively. DS3 and DS5 refer to the 30-min periods beginning 2 min after the tilts were initiated (the 2-min delay was implemented to avoid any artefacts due to the tilting procedure). DS6 refers to the final 30-min steady-state period in the upright position.

A comparison of steady-state values was then made between similar conditions during the tilt trials. Specifically, these were the supine position (DS4 during the ST and SI trials), the standing position (DS2 and DS6 during the ST trial), and the sitting position (DS2 and DS6 during the SI trial). These steady-state data were analysed by a one-factor analysis of variance for repeated measures to determine differences in the values of T, HF, MR, TC, and SW (using SuperAnova Statistical Programme for General Linear Modelling, Abacus Concepts, Berkeley, Calif.). When the F-ratio proved significant, the mean contrast test was applied to locate significance between the means using the Greenhouse-Geisser adjusted P-value. The level of statistical significance was set at $P < 0.05$ and where mean values are reported, the SE is given in parentheses.

Results

During all trials, the ambient conditions remained stable. Ambient temperature ranged from 28.2 to 28.5°C and did not change significantly during any exposure, and there were no differences among the various trials. Relative humidity was maintained between 38% and 42%. The average temperature difference between the rectal thermistors 1 (tip) and 3 was 0.20 (0.02) °C. No differences in this range were found between postures.

Control trial

Figures 2 and 3 show the mean values of body temperatures, MR, and $\overline{HF}$ for DS1 through DS6 during the last 3 h of the CN trial in the supine position (open circles). PC_1 and PC_2 values among subjects ranged from 0.02 to 0.05 and 0.03 to 0.08°C, respectively; mean (SE) values were 0.034 (0.003) and 0.047 (0.004) °C. The increase in T_{re} over time [from 36.75 (0.08) to 36.86 (0.06) °C], although small, is significant. Concurrent with this increase is a small, but also significant, increase in $\bar{T}_{sk}$ [33.88 (0.09) to 34.03 (0.12) °C], resulting in a significant rise in $\bar{T}_b$ [36.18 (0.08) to 36.29 (0.07) °C].

Head temperature (T_{head}) appeared constant until the last hour of exposure when an increase of about 0.18°C occurred (10 out of the 11 subjects showed an increase). The overall trend [34.40 (0.10) to 34.59 (0.08) °C] is significant. Also significant are the increases in temperatures of the trunk [T_{trunk} from 34.54 (0.13) to 34.80 (0.13) °C], the upper arm [T_{uarm} from 33.39 (0.16) to 33.69 (0.14) °C], the upper leg [T_{uleg} from 33.78 (0.12) to 34.08 (0.14) °C], and the lower leg [T_{lleg} from 33.70 (0.18) to 34.00 (0.14) °C]. Interestingly however, the hand (T_{hand}) and foot (T_{foot}) temperatures decreased significantly over the same period [33.90 (0.17) to 33.37 (0.33) and 33.12 (0.29) to 32.61 (0.24) °C, respectively].

The two measured heat balance variables, MR and $\overline{HF}$, did not indicate any significant change over time; overall mean values were 47.7 (1.6) and 32.9 (0.5) $W \cdot m^{-2}$, respectively. Of the calculated heat balance variables, only E_{sk} showed a very small but significant increase over time, from 11.48 (0.09) to 11.59 (0.11) $W \cdot m^{-2}$. The overall mean value of $E + R$ was 15.2 (0.2) $W \cdot m^{-2}$, and coupled with the values of MR and $\overline{HF}$ lead to an overall mean heat storage of -0.30 (1.7) $W \cdot m^{-2}$.

Perception of TC and SW did not change throughout the CN trial. Mean values over the last 3 h were 5.10 (0.12) for TC, and 0.038 (0.023), 0.001 (0.001), 0 (0), 0.015 (0.015), and 0.189 (0.108) for SW of the underarm, forehead, chest, back, and hand, respectively. Subjects felt thermally comfortable and dry which is consistent with a state of thermal balance.

Standing and sitting trials

Mean times to reach steady state in the supine position following the first tilt from sitting and standing under the criteria described earlier were 92.6 (6.4) and 116.6 (5.1) min, respectively. Mean times to steady state following the second tilt back to the upright positions were slightly longer, 107.9 (11.4) and 124.1 (9.0) min, respectively. Mean total times on the TT were 269.3 (5.5) and 300.3 (18.9) min for the SI and ST trials, respectively.

Figures 2 and 3 also show the mean values of body temperatures (except for $\bar{T}_b$ which is dealt with in the Discussion), MR, and $\overline{HF}$ for DS1 through DS6 during the ST and SI trials [recall that DS1 in this case (closed circles) refers to the average value over the 3 h of the Supine-C determined for comparative purposes]. The SE is shown only for the CN values to avoid confusion. These are, however, representative of the variances found during the ST and SI trials except for the temperatures of the head and foot which exhibited about twice the variance found during the CN trial. Significant temperature changes occurred at most body sites upon a change in posture. In general, T_{re} and T_{hand} increased in the upright position while T_{trunk}, T_{uarm}, and T_{lleg} decreased. The overall $\bar{T}_{sk}$ decreased in accordance with the findings of Nielsen et al. (1939); however, these values between the ST and SI trials were not significantly different. In some cases, specific temperature changes were greater for the ST versus SI trials. For example, the increase in the steady-state T_{re} from supine to upright was about 54% higher for the ST trials. In other cases, the changes were greater for the SI trials, such as the 145% greater decrease in T_{lleg} (see Table 1 and Fig. 2 for more details).

Individual values of the changes in steady-state T_{re} ranged from -0.13 to -0.46, 0.16 to 0.69, -0.30 to -0.86, and 0.42 to 1.22°C when tilting from sitting to supine, supine to sitting, standing to supine, and supine to standing, respectively. Mean values in the steady-state postures were 36.81 (0.07) for Supine-C (DS1), 37.20 (0.07) during the first SI sitting (DS2), 36.88 (0.07) during SI supine (DS4), 37.32 (0.05) during the second SI sitting (DS6), 37.43 (0.09) during the first ST

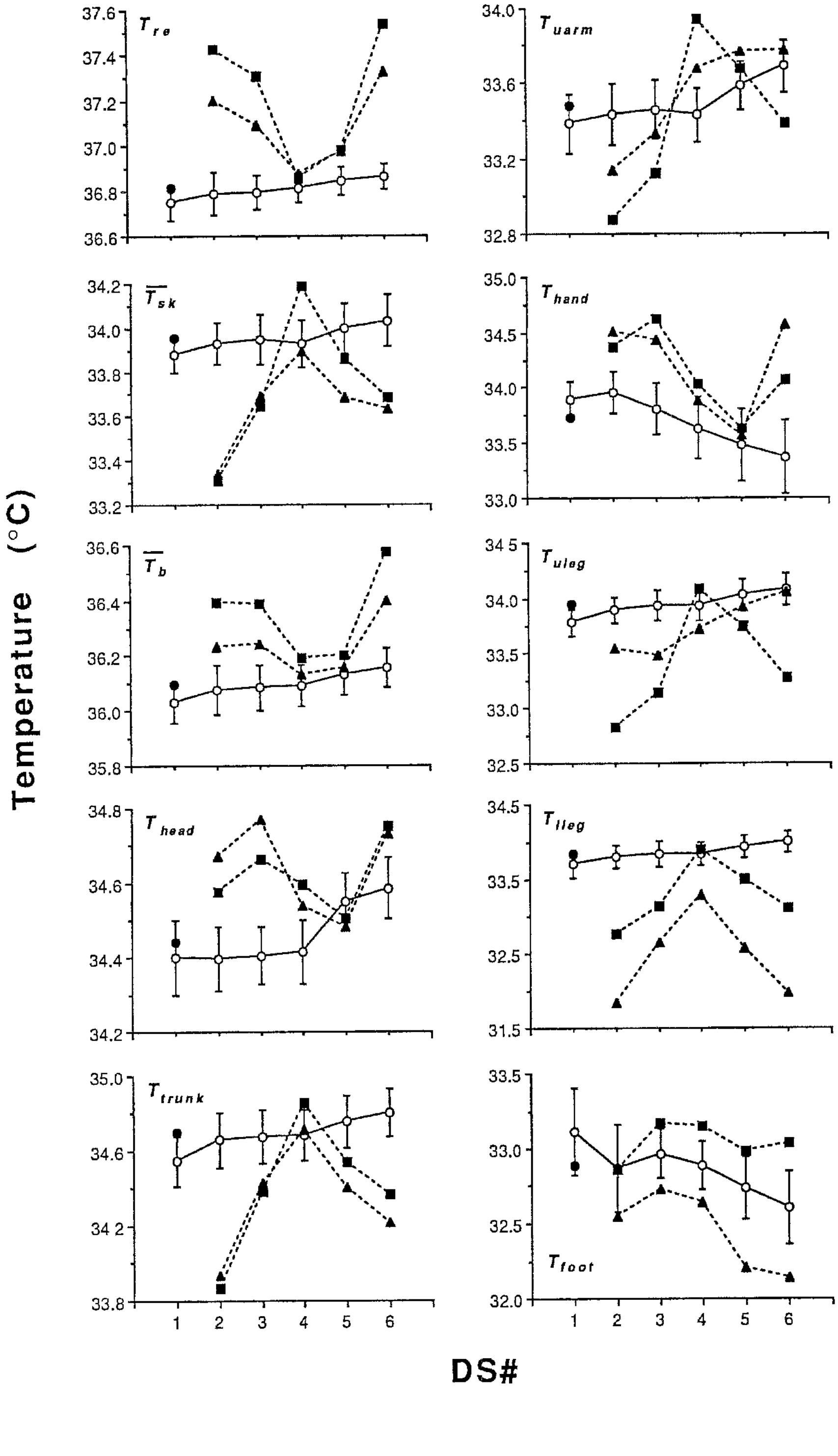

Fig. 2 Mean temperatures of various body sites during the control (CN, ○), sitting (SI, ▲), and standing (ST, ■) trials for 11 subjects in a thermoneutral air environment. The SE is shown only for the CN trials and DS1–6 refers to consecutive 30-min intervals during the last 3 h of exposure. DSI (●) of the SI and ST trials refers to the 3 h average of the CN values designated as SUPINE-C. DS2 and DS6 refer to the steady-state upright postures; DS3 and DS5 refer to the non-steady-state supine and upright postures, respectively; and DS4 refers to the steady-state supine posture (T temperature: T_{re} rectal, $\overline{T}_{sk}$ mean skin, $\overline{T}_{b}$ mean body, T_{uarm} underarm T_{uleg} upper leg, T_{lleg} lower leg)

standing (DS2), 36.86 (0.07) during ST supine (DS4), and 37.54 (0.10) during the second ST standing (DS6).

There were no changes in the heat production (MR) and heat loss [$\overline{HF}$, $(E + R)$] variables across all steady-state periods. Further, no differences in any of the variables were found between similar conditions at steady state. Therefore, the data were combined to obtain averages for each subject and then arranged in groups designated as Supine-T, Standing, and Sitting. Note that both Supine-T and Supine-C pertain to the supine position but for different trials (i.e. ST + SI tilt and CN control trials, respectively). Table 1 shows the mean (SE) of several of the measured and calculated variables and indicates that S was not different from zero at steady state. It was further determined that there were no differences in any of the variables between the Supine-C and Supine-T values. Therefore, another subject average value was made by combining the subject's Supine-C and Supine-T values with equal weighting under the designation Supine-A. Statistical

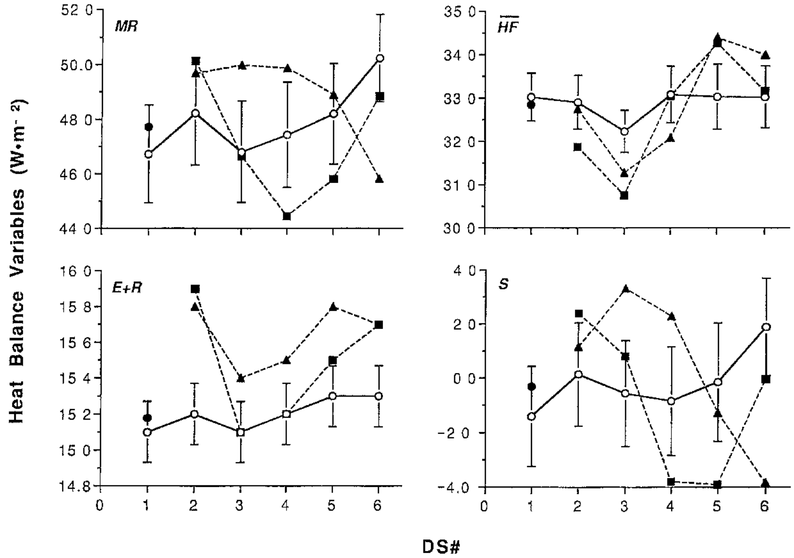

Fig. 3 Mean values of metabolic rate (MR) and mean-weighted heat flux ($\overline{HF}$) during the CN (○), SI (▲), and ST (■) trials for 11 subjects in a thermoneutral air environment. The SE is shown only for the CN trials and DS1–6 refers to consecutive 30-min intervals during the last 3 h of exposure. DSI (●) of the SI and ST trails refers to the 3 h average of the CN values designated as Supine-C. DS2 and DS6 refer to the steady-state upright postures; DS3 and DS5 refer to the non-steady-state supine and upright postures, respectively; and DS4 refers to the steady-state supine posture ($E+R$ sum of heat loss, S heat storage)

Table 1 Mean (SE) of the steady-state temperatures (°C), heat balance (W · m^{-2}), and thermal sensation variables during steady-state for 11 subjects in a thermoneutral air environment. (T temperature: T_{re} rectal, $\bar{T}_{sk}$ mean skin, $\bar{T}_b$ mean body, T_{uarm} underarm, T_{uleg} upper leg, T_{lleg} lower leg, MR metabolic rate, $\overline{HF}$ *mean-weighted heat flux*, ($E+R$) sum of heat loss, S heat storage, TC thermal comfort, $\overline{SW}$ mean skin wetness)

Variable	Supine-C	Supine-T	Standing	Sitting
T_{re}	36.81 (0.07)	36.87 (0.07)	37.47 (0.09)*	37.26 (0.05)**
$\bar{T}_{sk}$	33.95 (0.11)	34.04 (0.14)	33.48 (0.14)*	33.49 (0.10)*
$\bar{T}_b$	36.24 (0.08)	36.30 (0.07)	–	–
T_{head}	34.44 (0.08)	34.57 (0.10)	34.64 (0.12)	34.70 (0.09)
T_{hand}	33.73 (0.23)	33.96 (0.15)	34.24 (0.15)*	34.55 (0 10)*
T_{foot}	32 89 (0.16)	32.90 (0.25)	32.94 (0.40)	32.35 (0.31)
T_{trunk}	34.70 (0.14)	34.79 (0.10)	34.11 (0.20)*	34.07 (0.15)*
T_{uarm}	33.48 (0 14)	33.81 (0.15)	33.10 (0.15)*	33.46 (0.14)**
T_{uleg}	33.94 (0.14)	33.90 (0.15)	33.04 (0.15)*	33.80 (0.12)**
T_{lleg}	33.84 (0.15)	33.59 (0.16)	32.90 (0.23)*	31.91 (0.12)***
MR	47.74 (1.57)	47.17 (1.28)	49.25 (1.71)	47.75 (0.76)
$\overline{HF}$	32.86 (0.53)	32.57 (0.48)	32.47 (0.87)	33.38 (0.73)
$(E+R)$	15.18 (0.17)	15.37 (0.18)	15.80 (0.27)	15.71 (0.14)
S	– 0.30 (1.73)	– 0.77 (1.30)	0.98 (1.62)	– 1.34 (1.21)
TC	5.10 (0.12)	5.02 (0.07)	5.21 (0.15)	5.14 (0.14)
$\overline{SW}$	0.05 (0.03)	0.02 (0.01)	0.15 (0.08)	0.03 (0.02)

*Significant difference with the combined supine values (Supine-A; see text), ** significant difference with the Standing values

comparisons of all variables were then made between these values and those of Standing and Sitting. In essence, this allowed comparisons to be made among the three different postures during all steady-state conditions.

Table 1 also shows where differences in the variables occurred among these conditions. For example, the differences in T_{re} among the three postures were highly significant ($P < 0.003$) . T_{re} was about 0.2 and 0.6°C higher in the standing position than in the sitting and supine positions, respectively. $\bar{T}_{sk}$ was different between the upright (standing and sitting) and supine positions, but not between the two upright positions. No differences were found for T_{head} and T_{foot} while the hand and trunk indicated significant differences between the upright and supine positions, but not between the two upright positions. T_{uleg} was different in all positions, as it was for T_{uarm} and T_{uleg} except between Supine-A and Sitting.

Discussion

Body temperatures

The significant rises in T_{re} and $\bar{T}_{sk}$ over time (0.046 and 0.060°C · h^{-1}, respectively) during the CN trial concur with the expected rise due to the circadian rhythm (Aschoff 1983; Aschoff et al. 1974), however, no changes in thermal balance were perceived. T_{hand} and T_{foot} dropped progressively during the CN trials while $\bar{T}_{sk}$ increased (see Fig. 2), as observed by Aschoff et al. (1974) under similar thermoneutral conditions. The drop in T_{hand} also concurs with the observation of Cranston et al. (1954) who reported a progressive drop in HF from the hand for the supine position. In addition, these investigators also reported a continued drop in HF in the hand upon standing which we also found, but this was followed by a reversal which took place when steady state was attained [respective values of hand HF for DS4, DS5 and DS6 were 37.6 (1.3), 34.5 (1.5), and 37.2 (1.6) $W \cdot m^{-2}$]. Note that these HF were synchronous with the changes in the T_{sk} of the hand (see Fig. 2).

T_{head} tended to increase in unison with the increase in T_{re} in the upright postures (although the large variability in T_{head} indicated no change). This is consistent with the fact that T_{head} is largely influenced by arterial blood temperature via core temperature and that vasomotor control is minimized for the skin in the head (Day 1968). Kleitman and Doktorsky (1933) concluded that increased heat production due to an increase in muscle tonus contributes to the increase in T_{re}. However, the increase in MR in our study was not significant probably because the additional metabolic activity required for maintaining upright balance through muscular control was nearly eliminated by having the subjects lean 7.5° away from vertical against the TT.

An alternative factor responsible for the increase in T_{re} is offered by the explanations of Amberson (1943), Cranston et al. (1954), Nielsen et al. (1939), Shiraki et al. (1987), and Tanabe and Shido (1994). The decrease in T_{sk}, especially notable in the legs (see Fig. 2), reflects a decrease in cutaneous blood flow due to an orthostatic vasoconstriction in response to the drop in blood pressure upon tilt to the upright posture (Amberson 1943; Rowell 1986; Tanabe and Shido 1994; Zoller et al. 1972). This decrease in blood flow lessens the cooling effect of the venous blood return to the core, thus leading to an increase in T_{re} (Collins et al. 1982; Mittleman and Mekjavic 1988). If tilting could be accomplished without altering the hydrostatic stress on the body, then no change in blood flow should occur, and thus T_{re} should remain unchanged (provided that heat production also remained unchanged).

To explore this further, we conducted an exploratory study whereupon one subject was immersed up to the neck in a mildly stirred water bath at thermoneutrality (35.6–35.7°C). The subject began in a standing position secured against a slightly inclined platform fitted with a foot rest. Following the same criteria guidelines for tilting during the air trials, the subject attained a steady-state T_{re} of 37.19°C in the standing position after 85 min of immersion. The subject was then tilted while on the platform into a supine position (with only the face out of the water) and his T_{re} remained stable (between 37.17 and 37.21°C) over the next 1 h. Because of the near-perfect compensation of hydrostatic pressure achieved with the surrounding water, the body did not require any orthostatic adjustment. Hence, blood flow distribution did not change. Coupled with the probable constancy of MR (not measured) since maintenance of posture was not a factor, thermal balance was preserved during the tilt in thermoneutral water. This demonstrates and concurs with Tanabe and Shido (1994) that posture per se is not responsible for body temperature changes.

Heat fluxes

Somewhat peculiar was the finding that $\overline{HF}$ did not change significantly over the CN period while $\bar{T}_{sk}$ did. It is noteworthy that changes in HF were synchronous with changes in T_{sk} at each measured site. This apparent anomaly can be reconciled by examining the magnitude of the changes involved. The mean measured increase in $\bar{T}_{sk}$ of 0.150°C over the CN period (3 h) should increase overall HF by about 1.1 $W \cdot m^{-2}$ [based on a heat transfer coefficient of 7.5 $W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$ (Tikuisis et al. 1991a)]. However, such an increase was below the variance in HF measurements and, therefore, could not be ascertained. The variance in T_{sk} measurements was considerably smaller (its coefficient of variation was at least an order of magnitude lower than that of HF – see Fig. 4 for an example). Such variations in HF were also noted by Aschoff et al. (1974).

Another peculiarity are the seemingly incompatible values of $\bar{T}_{sk}$ and $\overline{HF}$ after steady state was attained in the upright postures. Even if redistribution of blood flow enhances core heating through a reduced heat loss at the skin surface, this should be reflected by lower $\overline{HF}$ values at steady-state. That this was not the case while $\bar{T}_{sk}$ had decreased led us to investigate correlations between HF and T_{sk} at each measured site. Interestingly, when subjects were tilted into the upright position, all sites indicated a positive correlation except for those sites that were in contact with or in close proximity to the TT. That is, while T_{sk} decreased at the right scapula, upper section of the right arm, posterior left thigh, and left calf sites, their HF values increased. Consequently, such increases effectively cancelled the decreases measured at the sites not in contact with the TT and $\overline{HF}$ did not change. This phenomenon is demonstrated in Fig. 4 where HF and T_{sk} of the right scapula (in contact) and chest (not in contact) sites are shown for all steady-state positions. Note the similar changes in T_{sk} but the contrasting changes in HF. Theoretically, HF is governed by the product of a heat transfer coefficient and the difference between the T_{sk} and ambient temperatures (Sekins and Emery 1982). For HF to increase while T_{sk} decreases suggests

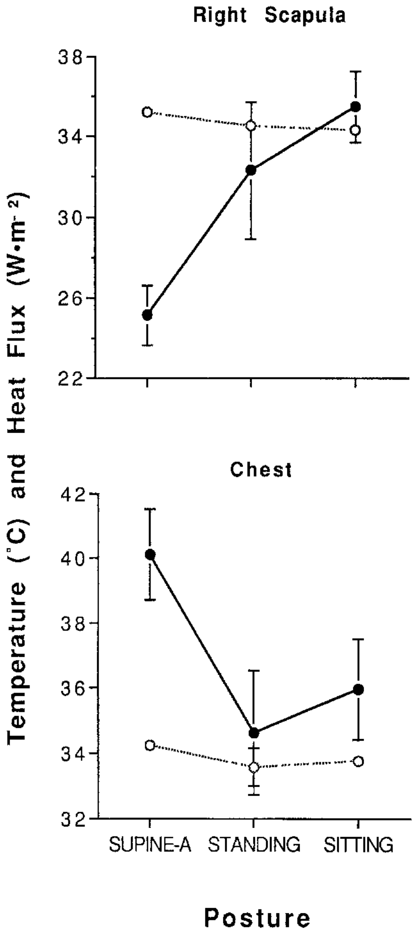

Fig. 4 Mean (SE) temperature (○) and heat flux (●) of the right scapula (in contact with the tilt table) and chest (not in contact) sites. Supine-A, Standing and Sitting refer to the average of all steady-state values in the supine, standing and sitting postures for 11 subjects in a thermoneutral air environment

that the heat transfer coefficient changed. Its value is dependent on the characteristics of the air boundary layer at the skin, and it is highly probable that the convective air movement increased in the upright position. The difference in the air boundary layers may be explained by the contact pressure which was likely higher in the supine position.

This also helps to explain the changes in $\overline{HF}$ during non-steady-state periods, first a decrease in the 30-min period following the tilt from upright to supine (DS3) and then an increase when returning to supine (DS5 - see Fig. 3). These changes were temporary and $\overline{HF}$ returned to its steady-state supine level. The initial decrease was probably driven by the reduced heat loss at the skin sites in contact with the TT upon assuming the supine position and the temporary increase following the second tilt (to upright) exposed those sites to an enhanced heat loss. Once steady state was reached with further respective increases and decreases in $\bar{T}_{sk}$, $\overline{HF}$ returned to its steady-state supine level.

Thermal balance

Significant increases in T_b, as measured during the control trials, imply a positive heat storage. In fact, assuming a mean body heat capacity of 0.99 $W{\cdot}h{\cdot}kg^{-1}{\cdot}{}^{\circ}C^{-1}$ (Sekins and Emery 1982) and applying the mean subject weight and height values of 81.0 kg and 179 cm, respectively [yielding an approximate surface area of 1.99 m^2 (DuBois and DuBois 1916)], the mean rate of $0.049^{\circ}C \cdot h^{-1}$ in $\bar{T}_b$ converts into a heat storage of nearly 2.0 $W \cdot m^{-2}$. Yet, the value of S determined through indirect calorimetry (-0.30 $W \cdot m^{-2}$) was not significantly different from zero. This slight disparity may be due to approximations made through the use of indirect calorimetry.

Thermal balance can occur at different values of body heat content; therefore, the attainment of thermal balance at steady state does not ensure that it is also preserved between changes in posture. To examine whether it is preserved, we consider only the changes in steady state T_b. First, it is noted that the increases in T_{re} and $\bar{T}_{sk}$ from the first to second steady state upright postures (i.e., DS6–DS2) are consistent with the circadian rhythm (Aschoff 1983; Aschoff et al. 1974). However, these increases, 0.038 and $0.089^{\circ}C \cdot h^{-1}$ for the SI and 0.028 and $0.094^{\circ}C \cdot h^{-1}$ for the ST trials, respectively, are relatively low for T_{re} and high for $\bar{T}_{sk}$ when compared to the increases found during the CN trials (0.046 and $0.060^{\circ}C \cdot h^{-1}$, respectively).

If thermal balance is preserved between tilts, then the circadian rate of change of T_b should also be preserved. Yet, it can be expected that the weighting coefficient (a) that determines $\dot{T}_b$, that is,

$$a = \frac{\dot{\bar{T}}_b - \dot{\bar{T}}_{sk}}{\dot{T}_{re} - \dot{\bar{T}}_{sk}} \tag{3}$$

also changes with posture due to vasomotor changes (Amberson 1943; Nielsen et al. 1939; Rowell 1986). Its value should decrease with increased vasoconstriction (Livingstone 1967) which occurs with upright posturing. Assuming a value of 0.80 for a in the CN trial (see Eq. 1) leads to a rate of change in $\bar{T}_b$ of $0.049^{\circ}C \cdot h^{-1}$. Equating this value to $\dot{\bar{T}}_b$ in Eq. 3 for the upright positions allows an estimation of a for these positions. For example, applying the values of $\dot{T}_{re}$ and $\dot{\bar{T}}_{sk}$ between steady states in the sitting position (0.038 and $0.089^{\circ}C \cdot h^{-1}$, respectively) leads to $a = 0.78$. Similarly, applying the respective values of 0.028 and $0.094^{\circ}C \cdot h^{-1}$ leads to $a = 0.68$ for the standing posture. These decreases in a from supine to upright postures, although modest for the sitting position, are consistent with increased levels of vasoconstriction found during cold exposure (Livingstone 1967). Although speculative, this indirectly supports the hypothesis that thermal balance is invariant to postural changes.

Conclusion

It is recognized that an absolute state of thermal balance cannot be attained, even during steady state, due to the circadian effect. The criteria formulated herein to declare a condition of steady state based on T_{re} were derived from the CN trials which were seen to display long-term, albeit small, increases in T_b consistent with the circardian effect (Aschoff et al. 1974). Indirect calorimetry confirmed that a relative state of thermal balance was attained during the steady-state conditions in the various postures.

The changes in T_b that occurred upon postural shifts were significant and much larger than can be attributed to the circadian effect. Mean changes in steady-state T_{re} of 0.60 and 0.39°C from supine to standing and sitting, respectively, are of the order that is sometimes reported in experiments involving thermal stress. While it may not be practical to await an acceptable steady-state condition prior to an exposure (this study suggests that about 2 h is required), potential changes in T_b due to postural shifts should be taken into account. Since thermal balance appears to be invariant to posture, this variable should be further explored as a logical choice for testing significant changes in experiments that may involve postural shifts.

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