# HEAT STORAGE DURING EXERCISE, ESPECIALLY IN MUSCLE

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## INTRODUCTION

Heat is stored and held in the body during exercise as evidenced by the rise in body temperatures. To be able to relate change in body heat content (Hb) to changes in body temperature one must have quantitative data fiom direct and indirect calorimetry. I have collected such data in past studies (1,2). From known body heat storage ($H_b$) during the onset of exercise obtained calorimetrically, the change in "mean body temperature" ( $\Delta\bar{T}_b$ ) is:

$$\Delta\bar{T}_b = H_b / m_b \cdot cp \qquad [1]$$

where $m_b$ is body mass (kg), and cp is specific heat of a subject's body (kJ/kg) from body composition (3)

Calculating weighting factors for change in rectal temperature (Tre) and change in mean skin temperature ( $\Delta\bar{T}_{sk}$ ) that would predict the known $\Delta\bar{T}_b$ , failed completely to find anything consistent or useful. Since muscle is where the extra heat is produced, it made sense to try to find a way to include it as a third temperature from which $\Delta\bar{T}_b$ could be predicted, so I used muscle temperature data fiom the literature, but again without success. Then, by trial and error some weighting coefficients were found that could be used to predict reasonable muscle temperature ($T_{mu}$) changes. These coefficients are presented.

## METHODS

Fifteen men and 5 women performed 72 walking experiments, level, uphill and downhill on the treadmill. External work (W) in uphill and downhill walking was calculated from treadmill speed and grade, and body weight. Subjects wore a suit Calorimeter (4) for direct measurement of heat loss ( $\dot{Q}_H$ ) and either a ventilated full facemask for measuring heat production ( $\dot{M}$ ) or worked in a respiration chamber. The suit calorimeter cooled subjects so that they sweated minimally. Experiments were continued until there were steady states of $\dot{M}$, $Q_H$ and body temperatures. $\dot{M}$ reached steady state quickly but $Q_H$ slowly.

Thus, while $Q_H$ was catching up to $\dot{M}$ , heat was stored in the body.

During this 40 – 70 min period, body heat storage was the accumulated difference between Total Heat ($H_{TOT}$), which is M – (±W), and $Q_H$.

## RESULTS

The basic measurements are summarized in Table 1, along with the calculated $\Delta\bar{T}_b$ for each exercise condition. All exercises were fiom walking on a treadmill at the speeds shown, either level (0 grade), uphill or downhill. The horizontal load shown for walking at **4.7 km/hr** 0 grade was a backpull with a weight to create positive work of **80** watts. The 20 kg vertical load when walking downhill at –15% raised the negative work to 200 watts.

In an effort to relate change in the two body temperatures that were measured to change in (known) mean body temperature, I used weighting factors of 0.9(Tre) and **0.1(** $\Delta\bar{T}_{sk}$ **)** with the standard equation:

$$\Delta\bar{T}_b = 0.9(T_{re}) + 0.1(\Delta\bar{T}_{sk}) \qquad [2]$$

The results were nonsense. I also tried solving for the weighting factor **"a"** in the following expression, **as** derived in a previous report (3):

$$a = (\Delta\bar{T}_b - \Delta\bar{T}_{sk}) / (T_{re} - \Delta\bar{T}_{sk}) \qquad [3]$$

**This** gave values over a huge range, from 12.49 to **–7.18,** but most values in the range ***of*** 2 to 4. The negative change in skin temperature and the use of a 2-compartment model produced these bizarre and useless values. In exercise the big change in heat production and heat storage is in a third body compartment, the skeletal muscle. Since I did not have measurements of muscle temperature, I used muscle temperatures fiom the literature for both negative and positive W, and plotted **these** as a **function** of Htot. Using this to predict **muscle** temperatures in the current experiments, and also using the equation of Nadel et al ***(5)*** to relate the 3-compartment temperature changes to $\Delta\bar{T}_b$ gave results that did not at all match the known $\Delta\bar{T}_b$ in **my data** (Table 1).

By assuming a fixed weighting of **skin** temperature at **0.1,** I could write the following equation:

$$\Delta\bar{T}_b = x(T_{re}) + (1-x)(T_{mu}) + 0.1(\Delta\bar{T}_{sk}) \qquad [4]$$

Solving for muscle temperature:

$$T_{mu} = (\Delta\bar{T}_b - x(T_{re}) + .1(\Delta\bar{T}_{sk})) / x \qquad [5]$$

With trial values for **X,** and using the basic data in table 1, values for Tmu were derived. Reasonable values for $T_{mu}$ came from x = 0.5 for level and uphill walking and **X =** 0.3 for downhill walking. Estimated $T_{mu}$s are shown in Table 2. Using these *two* values for the **X** coefficient, eq. [4] becomes:

**Level & uphill walking.** $\Delta\bar{T}_b = 0.5(T_{re}) + 0.4(T_{mu}) + 0.1(\Delta\bar{T}_{sk})$ [6]

**Downhill walking.** $\Delta\bar{T}_b = 0.3(Tre) + 0.6(Tmu) + 0.1(\Delta\bar{T}_{sk})$ [7]

**Table 1. Conditions and measurements; mean data**

| | n | $H_{TOT}$ | $Q_H$ | $\Delta H_b$ | $\Delta \overline{T}_b$ | $\Delta T_{re}$ | $\Delta \overline{T}_{sk}$ |
|---|---|---|---|---|---|---|---|
| | | kJ | kJ | kJ | °C | °C | °C |
| **Walking speed at 0% grade:** | | | | | | | |
| 25 km/hr | 6 | 1079 | 874 | 205 | 0.90 | 0.6 | -0.6 |
| 4.6 " | 7 | 1318 | 1046 | 272 | 1.23 | 0.7 | -2.0 |
| 4.7 " w/horiz.load | 9 | 2286 | 1871 | 415 | 1.77 | 1.1 | -3.0 |
| **Walking 5.4 km/hr:** | | | | | | | |
| Grade 10% | 8 | 2371 | 1857 | 514 | 2.01 | 1.3 | -0.8 |
| " 5% | 9 | 1841 | 1541 | 300 | 1.18 | 1.1 | -2.3 |
| " 0% | 8 | 1220 | 1063 | 157 | 0.60 | 0.3 | 0.7 |
| " -5% | 7 | 1445 | 945 | 500 | 1.94 | 0.5 | -0.5 |
| " -10% | 8 | 2000 | 1006 | 994 | 3.87 | 0.5 | -0.8 |
| " -15% w/vert. Load | 10 | 2829 | 1232 | 1598 | 6.22 | 0.5 | -0.25 |

**Table 2. Data from Table 1 plus estimated change in muscle temperature**

| | n | $\Delta H_b$ | $\Delta \overline{T}_b$ | AT, | $\Delta \overline{T}_{sk}$ | Estim. $\Delta T_{mu}$ |
|---|---|---|---|---|---|---|
| | | kJ | °C | "C | °C | "C |
| **Walking speed, 0 grade:** | | | | | | |
| 25 km/hr | 6 | 205 | 0.90 | 0.6 | -0.6 | 1.35 |
| 4.6 " . | 7 | 272 | 1.23 | 0.7 | -2.0 | 1.70 |
| 4.7 " w/horiz. load | 9 | 415 | 1.77 | 1.1 | -3.0 | 23 |
| **Walking 5.4 km/hr** | | | | | | |
| Grade 10% | 8 | 514 | 2.01 | 1.3 | -0.8 | 3.2 |
| " 5% | 9 | 300 | 1.18 | 1.1 | -2.3 | 1.0 |
| " 0% | 8 | 157 | 0.60 | 0 3 | 0.7 | 1.3 |
| " -5% | 7 | 500 | 1.94 | 0.5 | -0.5 | 2.9 |
| " -10% | 8 | 994 | 3.87 | 0.5 | -0.8 | 6.1 |
| " -15% w/vert. Load | 10 | 1598 | 6.22 | 0.5 | -0.25 | 10.1 |

## DISCUSSION

These are the first experiments with direct calorimetric measurements **of** $H_b$ during exercise. It was tempting to try to relate changes in body temperatures to $H_b$, even though there were no measurements made **of** muscle temperature.

Weighting coefficients were found for both positive and negative work that gave reasonable estimates of what $T_{mu}$ should be. The weighting coefficients found for $T_{mu}$ are large: **0.4** for positive work, 0.6 for negative work, suggesting that most heat storage during exercise is in muscle. An unusual aspect of this data: skin temperatures during exercise went down instead of rising because of the way the suit calorimeter was controlled. There was enough cooling to allow work without sweating, a pleasant sensation for the subjects, but not the usual case physiologically.

The estimates of change in muscle temperature were quite large for negative work, but this is reasonable because walking downhill results in a power input that immediately becomes heat in the muscles, which are being forcibly stretched as they try to contract. The estimates of muscle temperature here need **to** be tested against direct measurements made during exercise when there is also direct measurement of body heat storage.

## REFERENCES


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