The Human Body

Heat Balance in the Human Body

Lecture Notes
Question

How much energy does our body use, per second, or in a day?

How do we keep cool when it is really hot out?

Can we justify eating more when studying?
Big Ideas

• We assume are bodies are at a constant mass, and we are thus in a steady state condition: $\text{Power in} = \text{Power Out}$, averaged over a day or two.

• The body maintains the power balance with the environment by eating, clothing and sweating.
Background

• Homeotherms regulate their internal body temperature to an almost constant value at various environmental temperatures.

• We can understand how they do this by examining their power balance:

\[ M + R = C + \lambda + G + S \]
Power Balance

\[ M + R = C + \lambda + G + S \]

- \( M \) - metabolic rate,
- \( R \) - power transferred from radiation
- \( C \) - power transferred through convection,
- \( \lambda \) - power lost through the evaporation of sweat,
- \( G \) - power transferred through conduction
- \( S \) - power stored.

- \( R, C, G \) and \( S \) may have negative values.
- We assume \( S \) is negligible compared to the other quantities (healthy state for a mammal).
Calculating $M$:

- Metabolic rate = rate of energy production
- Glucose from food is oxidized to release heat as energy of metabolism:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2 + 686 \text{ kcal}$$

1 food cal = 1 kcal $\approx$ 4200 J
1 mol of sugar = 180 g

$$\therefore 1 \text{ g of sugar} = \left( \frac{686 \text{ kcal}}{180 \text{ g}} \right) \left( \frac{4200 \text{ J}}{1 \text{ kcal}} \right) = 16,000 \text{ J}$$
Calculating $M$

• The Basal Metabolic Rate (BMR) or $M_B$ is the energy the body consumes when it is completely at rest (i.e. if you were lying in bed all day).
• It is the energy required to perform all critical body functions such as breathing and circulation.

$$M_B \propto m^n$$

$m$ is the mass and the exponent $n$ lies between 2/3 and 3/4.
Calculating $M$

- Energy used for basal metabolism becomes heat.
- This heat is mainly dissipated through the skin.
- Thus, $M_B$ is approximately proportional to the surface area of the animal.
- For animals of different size but the same shape, $n = 2/3$:

$$M_B \propto 60\left(\frac{A}{m^2}\right) \, \text{W}, \quad A = \text{area}(m^2)$$
Calculating $M$

• For humans, the mean surface area is approximately 1.7 m² so $\text{BMR} \approx 100$ W

• Any exercise on top of this requires more power (i.e. $M$ is usually $> \text{BMR}$).

• To maintain this steady flow of heat from the human body's core (37 C) to the environment, the skin has to have a temperature of about 33 C.
Calculating $M$

- A person's mass is a balance between their caloric intake and energy expenditure.
- Different foods (carbohydrates, proteins and fats) have different caloric values;
  - If energy consumed < energy expended, a person loses weight
  - If energy consumed > energy expended, a person gains weight
Calculating $M$

- When the body has used the energy from all of the consumed food, it then starts using up your energy stores.
- There is thus a need to balance your energy consumption with energy expenditure.
Calculating $M$ during Activities

The power used during an activity depends on:

a) Person’s weight (heavier = more power)
b) Intensity of the activity

<table>
<thead>
<tr>
<th>Activity</th>
<th>Calories/hr*</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeping</td>
<td>60</td>
<td>0.07</td>
</tr>
<tr>
<td>Walking (5 km/hr)</td>
<td>280</td>
<td>0.3</td>
</tr>
<tr>
<td>Water Aerobics</td>
<td>300 - 500</td>
<td>0.3 – 0.6</td>
</tr>
<tr>
<td>Skating</td>
<td>300 - 600</td>
<td>0.3 – 0.7</td>
</tr>
<tr>
<td>Swimming</td>
<td>300 - 600</td>
<td>0.3 – 0.7</td>
</tr>
<tr>
<td>Running</td>
<td>400 - 700</td>
<td>0.5 – 0.8</td>
</tr>
<tr>
<td>Biking</td>
<td>450 - 700</td>
<td>0.5 – 0.8</td>
</tr>
</tbody>
</table>

* Values for a 65 kg woman. A 90 kg man would burn 1.5 times more calories doing the same exercise at the same intensity.
Calculating $M$ while a person is thinking

To find the energy expended and consumed while thinking, participants were surveyed on two different days, in different situations:

<table>
<thead>
<tr>
<th></th>
<th>Day 1: 45 mins spent sitting idle in a chair</th>
<th>Day 2: 45 mins spent reading and summarizing an article</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy expended</td>
<td>$\sim 60 \text{ kcal}$</td>
<td>$\sim 85 \text{ kcal}$</td>
</tr>
<tr>
<td>Food (kcals) consumed after*</td>
<td>900 kcal</td>
<td>1150 kcal</td>
</tr>
</tbody>
</table>

* Both times participants indicated similar levels of hunger
Calculating $M$ while a person is thinking

• Difference in the energy expenditure of sitting vs. studying = 25 kcal

• Difference in the food consumed afterwards was 250 kcal! i.e those who read/summarized ate 250 more kcal than those who didn’t.
Why do you feel more hungry when you study?

• Thinking requires glucose → the body stores this as glycogen in the blood and converts it back to glucose, to use it.

• While thinking, your brain quickly depletes the glucose stores in your blood, and tells you unconsciously to eat so that you can return the glucose levels to normal.

• Thus, you eat more while you study, even though you don't necessarily feel hungry.
Calculating $R$: Introduction

• The total radiation power absorbed from the environment is $R$
• This is the sum of longwave and shortwave radiation:

$$ R = R_L + R_S $$

• Shortwave radiation, $R_S$, comes from direct sunlight (both visible and near infrared)
Calculating $R$: Longwave Radiation

- Longwave radiation is from the local environment e.g. thermal radiation from buildings, the ground, flora and the sky.
- It is calculated using the following formula:

$$Q = A \varepsilon \sigma (T_{\text{skin}}^4 - T_{\text{env}}^4)$$

- $A = \text{surface area of the body}$
- $\varepsilon = \text{emissivity of the skin (~0.98)}$
- $\sigma = \text{Stefan Boltzman Constant}$
- $T_{\text{skin}} = \text{temperature of the skin}$
- $T_{\text{env}} = \text{temperature of the environment}$
Calculating $R$:

If $T_{\text{skin}} > T_{\text{env}}$, $Q$ is $+$ve; you radiate heat into the environment.
If $T_{\text{skin}} < T_{\text{env}}$, $Q$ is $-$ve; you absorb heat radiated from the environment.

Short wave radiation coming from the sun (up to $1 \text{ kW/m}^2$ or more on a clear day on an area facing the sun directly).
Calculating $R$: 54 C in Baghdad

The temperature in Baghdad, Iraq hit 54 C in August 2010. What does this do to the radiation balance of the human body?

Conditions:
- You are indoors
- $T_{\text{skin}} = 306 \text{ K}$
- $T_{\text{env}} = 327 \text{ K}$

Thus: $R_L \approx 340 \text{ W}$
Calculating $R$: 54 C in Baghdad, Indoors

The temperature in Baghdad, Iraq hit 54 C in August 2010. What does this do to the radiation balance of the human body? Assume you are indoors.

For:

$T_{\text{skin}} = 306$ K and $T_{\text{env}} = 327$ K,

$R_L \approx 340$ W
Calculating $R$: 54 C in Baghdad, Outside

What if you went outside?

Sunlight = 1 kW/m$^2$
Area of the body facing the sun $\approx 0.5$ m$^2$
Clothing/skin absorbs $\approx 50\%$ of the light

The power absorbed from the sun is:

$$R_s = (0.5)(1000 \frac{W}{m^2})(0.5 \text{ m}^2) = 250 \text{ W}$$
Calculating $R$: 54 C in Baghdad, Outside

- 250 W is a big heating load to bear
- It gets worse since we also need to consider convection - convection is not going to cool us in these circumstances.
Calculating $C$, Power Losses through Convection

Convection: transfer of heat by gas or liquid in motion (in our case, between skin and the surrounding air). It is dependent on:

a) $\Delta T$ between skin and air
b) Speed of the air

$$C = K_C A(T_{skin} - T_{env})$$
Calculating $C$: How wind speed affects $K_C$

- $K_C$ is an empirical factor that applies to the geometry of the human body.
- It varies with speed of air:

<table>
<thead>
<tr>
<th>Speed of Air</th>
<th>$K_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Still air, 0 m/s</td>
<td>3 W/m²/k</td>
</tr>
<tr>
<td>2 m/s</td>
<td>26 W/m²/k</td>
</tr>
<tr>
<td>10 m/s</td>
<td>37 W/m²/k</td>
</tr>
<tr>
<td>20 m/a</td>
<td>41 W/m²/k</td>
</tr>
</tbody>
</table>
Calculating $C$: How wind speed affects $K_C$

- The largest difference in $K_C$ values is between still and moving air.
- Not much difference between $K_C$ values at different speeds of moving air.
- For $\Delta T$ of 5K:
  - Power transferred at 0 m/s = 20W
  - Power transferred at 2 m/s = 200W
Calculating $C$:

Why do we cool down when the wind blows?

- Our body warms a thin layer of air on our skin as insulation, called the “Boundary Layer”
- Wind blows this layer away.
- Our bodies thus use energy to re-create this layer.
- If the layer keeps blowing off, our skin temperature drops and we feel cooler.
- A wind speed of just 2 m/s is enough to blow away the boundary layer.
Calculating $\lambda$, the Evaporative Loss:

Latent Heat of Vaporization of water: the amount of energy absorbed as water changes from liquid to a gas. At $30^\circ C \approx 2.4$ MJ/L

- Sweat is our body’s primary cooling mechanism - We cool down when sweat evaporates off our skin
- The energy to evaporate sweat, the latent heat of vaporization, is provided by our body.
Calculating $\lambda$, the Evaporative Loss:

- We sweat a max. of 1L/h - 1.5 L/h
- 2.4 MJ is lost during evaporation of 1 L of sweat off our skin.
- Thus evaporative power losses are:

$$\lambda = \left(\frac{2.4 \text{ MJ}}{\text{L}}\right)\left(\frac{1 \text{ L}}{\text{h}}\right)\left(\frac{1 \text{ h}}{3600 \text{s}}\right) = 670 \text{W}$$
The Effect of Humidity On Sweating

• The higher the humidity, the more difficult it is for us to sweat – hot, humid days are more uncomfortable than hot, dry days.

• The closest we get to zero humidity is the Antarctic – 0.03%. At this humidity level, there is no barrier to sweat.

• Fortunately, it is quite cold in the Antarctic and our bodies don’t perspire much – we would sweat endlessly there!
Calculating $G$, Power losses through conduction

Conduction: transfer of heat from high temperature to a low temperature by direct contact with a solid, dependent on:

a) $\Delta T$ between skin and contact material

b) Thermal properties of the material

\[
G = \frac{KA(T_{\text{skin}} - T_{\text{env}})}{d}
\]

$K = \text{thermal conductivity (W/mK)}$

$d = \text{thickness of the material}$

$A = \text{surface area of body in contact with material}$
Calculating $G$

What would be the conduction losses from our feet, if we had on rubber flip-flops?

For a rubber (polyurethane) flip-flop:

$A = (20 \text{ cm})(30 \text{ cm}) = 0.06 \text{ m}^2$

$k = 0.02 \text{ W/mK}$

$d = 0.01 \text{ m}$

$T_{\text{skin}} = 306 \text{ K}$

$T_{\text{env}} = 293 \text{ K}$
Calculating $G$

What would be the conduction losses from our feet, if we had on rubber flip-flops?

$$G = \frac{(0.02)(0.06)(293 - 306)}{0.01}$$

$$G = 1.56 \text{ W}$$

A 1.56 W power loss through conduction to the floor through shoes is very small compared to all other energy flows.
Are Conduction Power Losses Always Negligible?

A story from Alcatraz…

• Prisoners in Alcatraz were stripped of their clothes and thrown into a cold concrete room, as punishment.

• With the large s.area of their bodies touching the concrete ($K_C$ of 0.3-1.7 W/mK), conduction losses (at 0°C) were several hundred W!
Are Conduction Power Losses Always Negligible?

A story from Alcatraz… (continued)

• To prevent these losses, they propped themselves off the ground, on toilet paper rolls

• With the small surface area now in contact with the rolls and the low $K_C$ of paper (0.05 W/mK), their conduction losses were greatly lowered
Bibliography


