Regulation of Body Temperature - Heat Exchange Mechanisms
Ultimately all energy produced as the result of metabolic processes appears as:

- mechanical work done on external environment
- thermal energy (heat)!

\[ \Delta U = Q + W \]

For homeothermic organism:

\[ \Delta T = 0 \rightarrow \Delta U = 0 \]
The Overall Thermal Effect of Chemical Reaction Depends Only On:

- The Initial $(U_1, H_1)$ and
- The Final $(U_2, H_2)$ State of the Substance!

The Thermal Effect is Independent Of:

- Forms and States of Transitional Chemical Compounds Which Are Originated During the Process, AND
- Series of States Through Which the System Passes.
Biological work

**EXTERNAL WORK**
- Energy from food intake
- Simple sugars
- Fatty acids
- Amino acids

**INTERNAL WORK**
- Chemical work
- Mechanical work
- Electrical work

**THERMAL ENERGY**

**CHEMICAL WORK** - REACTIONS OF SYNTHESIS, GROWTH AND MAINTAINNANCE OF CELL STRUCTURES

**MECHANICAL WORK** - CONTRACTION OF MUSCLE CELLS

**ELECTRICAL WORK** - TRANSPORTATION OF ELECTRICALLY CHARGED MOLECULES UPHILL AN ELECTRIC FIELD GRADIENT
<table>
<thead>
<tr>
<th>Body core temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nerve malfunction and brain damage</strong></td>
</tr>
<tr>
<td>45</td>
</tr>
<tr>
<td>44</td>
</tr>
<tr>
<td>43</td>
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<td>42</td>
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<tr>
<td>30</td>
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<tr>
<td>29</td>
</tr>
<tr>
<td>28</td>
</tr>
</tbody>
</table>

(From: Human Physiology, Vander, Sherman, Luciano)
Energy balance

To maintain constant body temperature ($\Delta T = 0$) all (!) thermal energy generated ($Q_{\text{produced}}$) inside a body must be released to environment ($Q_{\text{released}}$).

Energy imbalance leads to:

Hyperthermia: $\frac{Q_{\text{released}}}{\Delta t} < \frac{Q_{\text{produced}}}{\Delta t}$

Hypoerthermia: $\frac{Q_{\text{released}}}{\Delta t} > \frac{Q_{\text{produced}}}{\Delta t}$
To estimate value of the metabolic rate it is necessary to know:

- the rate of oxygen consumption and
- the amount of energy produced when unit volume of oxygen is consumed (i.e. the energy equivalent of oxygen)

For a mixed diet the average value of energy equivalent of oxygen is 20 kJ (kilojoule) per one liter of consumed O₂.
1. Age: children > adults.
2. Sex: males > females.
3. Muscular (physical) activity.
5. Pregnancy, lactation, menstruation.
6. Ingested food *(specific dynamic effect!)*.
7. Diseases and infections.
8. Mental activity and emotional stress.

<table>
<thead>
<tr>
<th>ACTIVITY</th>
<th>METABOLIC RATE (ENERGY PRODUCTION IN UNIT TIME)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kcal per square meter per hour</td>
</tr>
<tr>
<td><strong>REST</strong></td>
<td></td>
</tr>
<tr>
<td>Basal metabolism (standard men)</td>
<td>38</td>
</tr>
<tr>
<td>laying awake</td>
<td>40</td>
</tr>
<tr>
<td>Sitting upright at a lecture (awake)</td>
<td>102</td>
</tr>
<tr>
<td><strong>MODERATE ACTIVITY</strong></td>
<td></td>
</tr>
<tr>
<td>Walking at 5 km/h</td>
<td>135</td>
</tr>
<tr>
<td>Cycling at 5 km/h</td>
<td>195</td>
</tr>
<tr>
<td>Swimming breastsroke 1.6 km/h</td>
<td>230</td>
</tr>
<tr>
<td><strong>HEAVY ACTIVITY</strong></td>
<td></td>
</tr>
<tr>
<td>Cycling at 21 km/h</td>
<td>340</td>
</tr>
<tr>
<td>Harvard Step Test</td>
<td>550</td>
</tr>
<tr>
<td><strong>SHIVERRING !!!</strong></td>
<td>to 250</td>
</tr>
</tbody>
</table>
Basal Metabolic Rate (BMR)

is primarily affected by physical body characteristics and is usually estimated on the basis of a body mass \( m \).

\[ BMR = 70 \ m^{0.75} = 1700 \text{ kcal/day} \]

\[ BMR = 3.4 \ m^{0.75} = 82 \text{ W} \]
Maintenance of constant temperature of an object demands precise balance of heat sources against heat losses!

GAIN OF HEAT = LOSS OF HEAT

Energy from metabolism + Energy from environment + convection + radiation + conduction + evaporation
Mechanisms of Heat Exchange

- Conduction through body tissues
- Convection
- Radiation
- Evaporation

Warm blood from body core at 37°C

Vaso-motoric control
CONDUCTION of heat is the transfer of thermal energy (energy of random thermal motion) by electrons or by collisions of atoms or molecules.

\[ \Delta Q = \lambda \Delta x \]

\( \Lambda T = T_1 - T_2 \)

\( \frac{\Delta Q}{\Delta t} = -\lambda S \frac{\Delta T}{\Delta x} \)

THE FOURIER LAW:
Assume that the thickness of the tissue between the interior of the body is $\Delta x = 3 \text{ cm}$ and that the average effective area through which conduction can occur is $1.5 \text{ m}^2$; $\lambda = 0.2 \text{ W/m} \cdot \text{K}$.

\[ \frac{\Delta Q}{\Delta t} = - \lambda S \frac{\Delta T}{\Delta x} \]

Calculate the amount of heat conducted from the core to the shell in unit time (i.e. the power).

\[ \Delta Q/\Delta t = P = 30 \text{ W} \]

- The body gains or losses heat by conduction only through direct contact with warmer or cooler substances!

- The better the contact, the better exchange.

- The conduction of heat plays a significant role in carrying heat from the core of human body to the skin and is substantially greater when a human is immersed in the water than in the air.
The Stefan-Boltzmann law for thermal radiation from non reflecting body:

\[
\frac{\Delta Q}{\Delta t} = \varepsilon \sigma ST^4
\]

where:
- \( \Delta Q/\Delta t \) energy radiated in unit time (i.e. power \( P \)) by body of surface \( S \),
- \( T \) temperature of a body (in absolute scale),
- \( \sigma \) Stefan-Boltzmann constant,
- \( \varepsilon \) surface emissivity.

Net exchanged power:

\[
P_{\text{emitted}} - P_{\text{absorbed}} = \varepsilon \sigma S (T_{\text{skin}}^4 - T_{\text{environment}}^4)
\]

**THERMOGRAPHY:**
detection of infra-red radiation emitted by the skin to determine the distribution of temperature over the area of interest

Complex Regional Pain Syndrome in right foot. The right foot is 3.7 C colder than the left foot.
Determine the rate at which a naked human of a surface area 1.7 m\(^2\) (effective area is usually smaller, say 1.2 m\(^2\)) loses heat to walls which are maintained at 20 °C (68 °F).

The human body not only radiates but also absorbs the radiant energy. If we denote the environment temperature by \(T_e\) (20 = 293 K) and the temperature of a radiating object (for instance human skin) by \(T_s\) (34 °C = 307 K) the net power radiated is:

\[
P_{\text{net}} = 5.67 \times 10^{-8} \text{ W/mK} \times 1.8\text{m}^2 \times (307^4 \text{K}^4 - 293^4 \text{K}^4) = 154 \text{ W}
\]

188% of BMR
**Convection**

Heat transfer by mass motion of a fluid such as air or water when the heated fluid is caused to move away from the source of heat, carrying energy with it.

\[ \frac{\Delta Q}{\Delta t} = P = K_{\text{conv}} \cdot S \cdot (T_s - T_A) \]

- **\( K_{\text{conv}} \)** — coefficient that depends upon movement of the air (*),
- **\( S \)** — the effective surface area,
- **\( T_s \)** — temperature of the skin,
- **\( T_A \)** — the temperature of the convective fluid (air).

---

**Wind Chill Factor**

As the wind increases, it draws heat from the body (forced convection), driving down the skin temperature and eventually (by conduction) the internal body temperature. The wind therefore makes you feel much colder.

<table>
<thead>
<tr>
<th>Actual temperature (°C)</th>
<th>20</th>
<th>10</th>
<th>0</th>
<th>-10</th>
<th>-20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed, m/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equivalent temperature (°C)</td>
<td>20</td>
<td>10</td>
<td>0</td>
<td>-10</td>
<td>-20</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>10</td>
<td>0</td>
<td>-10</td>
<td>-20</td>
</tr>
<tr>
<td>5</td>
<td>17</td>
<td>5</td>
<td>7</td>
<td>-19</td>
<td>-31</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>1</td>
<td>-13</td>
<td>-27</td>
<td>-40</td>
</tr>
<tr>
<td>15</td>
<td>14</td>
<td>-1</td>
<td>-16</td>
<td>-30</td>
<td>-45</td>
</tr>
</tbody>
</table>
Determine the rate of heat lost due to convection in the following conditions:

1. still air, no wind
2. wind speed 2 m/s

Assume effective area \( S = 1 \text{ m}^2 \), air temperature: \( T_A = 25^\circ \text{C} \) and skin temperature: \( T_S = 33^\circ \text{C} \).

\[
P = K_{\text{conv.}} \cdot S \cdot (T_S - T_A)
\]

1. Resting body, no wind: \( K_{\text{conv.}} = 2.7 \text{ W/m}^2\text{C} \)
   \( P = 22 \text{ W} \) (27% of BMR)

2. Wind speed 2 m/s: \( K_{\text{conv.}} = 21 \text{ W/m}^2\text{C} \)
   \( P = 170 \text{ W} \) (207% of BMR)
Thermal energy is required to transform water from the liquid to the gaseous state. Thus whenever water vaporizes from the body surface, the heat required to drive the process is drawn from the skin - thereby cooling it.

\[ \frac{\Delta Q}{\Delta t} = P_{ev.} = K_{ev.} S (p_s - p_e) \]

where:
- \( p_s \) - partial pressure of water vapour at the skin surface,
- \( p_e \) - partial pressure of water vapour in the environment,
- \( K_{ev.} \) - proportionality coefficient,
- \( S \) - surface area.

- Evaporation of water from the skin and the lining membranes of the respiratory tract is one of major (!) processes responsible for the loss of body heat.
- Evaporation is the only effective process of heat removal if body temperature is equal or lower than the air and surrounding objects’ temperature.
Determine the rate at which energy is lost to evaporate 0.6 kg of water in 24 hours (insensible perspiration).

The amount of thermal energy necessary to transform 1 kg of water into water vapour (the heat of vaporization $Q_{ev.}$) at skin temperature is approximately equal to $2.4 \times 10^6$ J/kg.

\[
\text{power} = \frac{\text{energy}}{\text{time}} = \frac{\text{heat of evaporation} \times \text{mass of water}}{\text{time}}
\]

\[
P = \frac{Q_{ev.} \times m}{t} = \frac{2.4 \times 10^6 \text{ J/kg} \times 0.6 \text{ kg}}{24 \text{ hours} \times 3600 \text{ s}} = 17 \text{ W}
\]

**PERCENTAGE CONTRIBUTION:**
17W out of 82W equals 21% !
Heat formation by metabolism

Radiation and conduction gain of heat

Skin temperature 33°C

Heat loss by evaporation

Radiation and convection loss of heat

Vasomotoric regulation

Range of heat loss and increased metabolism

Sweating

Partition of heat exchange

VASOCONSTRICTION AND VASODILATION
### Summary of effector mechanisms in temperature regulation

<table>
<thead>
<tr>
<th>Desired effects stimulated by cold</th>
<th>Desired effects stimulated by heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>decreasing heat loss</td>
<td>increasing heat production</td>
</tr>
<tr>
<td>Vasoconstriction of skin vessels (increased secretion of epinephrine – α-adrenergic effect)</td>
<td>Increased muscle tone</td>
</tr>
<tr>
<td>Reduction of surface area (curling up etc.)</td>
<td>Shivering and resulting piloerection</td>
</tr>
<tr>
<td>Behavioral response (put on warmer clothes, raise thermostat settings)</td>
<td>Increased food intake</td>
</tr>
</tbody>
</table>
# Role of Circulation in Thermoregulation During Exercise

<table>
<thead>
<tr>
<th>Variables</th>
<th>Rest</th>
<th>Strenuous Exercise</th>
<th>Maximal Exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen Consumption (liters/min.)</td>
<td>0.25</td>
<td>1.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Metabolic rate (heat production) in kcal/min.</td>
<td>1.19</td>
<td>5.7</td>
<td>9.5</td>
</tr>
<tr>
<td>in watts</td>
<td>82</td>
<td>400</td>
<td>670</td>
</tr>
<tr>
<td>Cardiac output (liters/min)</td>
<td>5.8</td>
<td>17.5</td>
<td>25.0</td>
</tr>
<tr>
<td>Blood flow (liters/min.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skeletal muscle</td>
<td>1.2</td>
<td>12.5</td>
<td>22.0</td>
</tr>
<tr>
<td>Skin</td>
<td>0.5</td>
<td>1.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Vascular resistance (% of normal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skeletal muscle</td>
<td>100</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Skin</td>
<td>100</td>
<td>40</td>
<td>115 Vasoconstriction!</td>
</tr>
</tbody>
</table>

Metabolic rate = rate of oxygen consumption energy equivalent of oxygen!

\[
\text{Flow} = \frac{\Delta p}{R_V}
\]

\[
R_V = \frac{8\eta l}{\pi r^4}
\]

20kJ/liter = 4.77 kcal/liter

1 cal = 4.19J

1 J = 0.239 cal