2. THE ENERGY HOUSEHOLD OF THE BODY

2.2. ENERGY CONSUMPTION OF THE BODY
When no external work is done the lowest oxygen consumption rate is obtained, the internal energy diminishes at its lowest rate, BMR; the basal metabolic rate,

$$\frac{\Delta W}{\Delta t} = 0; \quad \text{BMR} = \frac{\Delta U}{\Delta t} \approx 70\text{kcal}/h = 81W;$$

The BMR is the rate at which the internal energy of the organism decreases while fasting and being completely at rest! Basal metabolic rate for all mammals correlates with the body mass $M$ (in the above example $M \approx 65$ kg):

$$\text{BMR} = \frac{\Delta U}{\Delta t} = C \cdot M^{3/4},$$

with $C \approx 90$ kcal/kg$^{3/4}$; Kleiber's Law

Kleiber’s law represents a biological scaling law which is physiologically justified by the argument that the basal metabolic rate is corresponds directly to the cross sectional area of the muscle mass in the mammal. This area varies with $M^{3/4}$. 
The basal metabolic rate reflects the rate at which each organ and part of the body does internal work! For example work done by

- heart (*pumping blood through the blood vessels*)
- lung (*breathing*)
- liver (*chemical processes*)
- kidney (*separating waste products*)
- brain (*thinking*)

\[
\text{BMR} = \frac{\Delta U}{\Delta t} = \frac{\Delta Q_{\text{heart}}}{\Delta t} + \frac{\Delta Q_{\text{lung}}}{\Delta t} + \frac{\Delta Q_{\text{liver}}}{\Delta t} + \frac{\Delta Q_{\text{kidney}}}{\Delta t} + \frac{\Delta Q_{\text{brain}}}{\Delta t} + \frac{\Delta Q_{\text{etc}}}{\Delta t}
\]

The following table lists the contributions of the various body organs to the BMR and the necessary rate of oxygen consumption:

<table>
<thead>
<tr>
<th>Organ</th>
<th>Rate of Energy Consumption (Expt.)</th>
<th>Percent of Basal Metabolic Rate</th>
<th>Rate of Energy Consumption (Theoretical)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(ml/min) (kcal/day)</td>
<td></td>
<td>(kcal/day)</td>
</tr>
<tr>
<td>Heart</td>
<td>17 117</td>
<td>~7%</td>
<td>140</td>
</tr>
<tr>
<td>Lung</td>
<td></td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Kidney</td>
<td>26 180</td>
<td>~10%</td>
<td>(.74/e) ≈ 180</td>
</tr>
<tr>
<td>Liver &amp; Spleen</td>
<td>67 470</td>
<td>~27%</td>
<td></td>
</tr>
<tr>
<td>Brain</td>
<td>47 325</td>
<td>~19%</td>
<td></td>
</tr>
<tr>
<td>Skeletal Muscle</td>
<td>45 310</td>
<td>~18%</td>
<td></td>
</tr>
<tr>
<td>(Remainder by difference)</td>
<td>48 328</td>
<td>~19%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>~250 1730</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

The brain constitutes only 2.5% of body weight, but is responsible for ≈ 20% of the BMR (dreams). It requires a fair amount of oxygen consumption.
All activities, from slow walking to race bicycling require the body to do external work:

$$\frac{\Delta W}{\Delta t} > 0$$

It also requires a higher rate of oxygen consumption and an increase in the metabolic (catabolic) rate $\Delta U/\Delta t$. The released internal energy $\Delta U$ is partly used to do the external work but converts partly into heat which is irradiated into the outer environment.

**Example:** Lecturing originates heat flow of 100 - 300 W/person

Figure shows an average heat production $M$ by change of internal energy of 390 kcal/hr = 453 W and an average heat loss $H$ of 260 kcal/hr = 300 W (assuming constant walking)
To compensate losses of internal energy associated with basal metabolism and daily activities daily food intake is necessary. People with limited body activities require (faculty members):

\[ \approx 150 \text{ kcal/hr} \cdot 12 \text{ hr} + 70 \text{ kcal/hr} \cdot 12 \text{ hr} = 2640 \text{ kcal/day} \]

A construction worker with a heavy work load requires:

\[ \approx 450 \text{ kcal/hr} \cdot 12 \text{ hr} + 70 \text{ kcal/hr} \cdot 12 \text{ hr} = 6240 \text{ kcal/day} \]

The losses of internal energy are also directly correlated with age! Figure shows losses normalized to body surface area A in units m\(^2\):

\[ A \approx 0.202 \cdot H^{0.425} \cdot M^{0.725} \]

with \( H \equiv \) height of body in [m]; \( M \equiv \) mass of body in [kg]

\[ 1 \text{ W/m}^2 \equiv 0.86 \text{ kcal/(hr} \cdot \text{m}^2) \]
### Example: Average Daily Internal Energy Consumption of a Middle Aged Faculty Member

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time Period [hr]</th>
<th>Catabolic Rate [kcal/min]</th>
<th>Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleep</td>
<td>10</td>
<td>1.2</td>
<td>720</td>
</tr>
<tr>
<td>Thinking</td>
<td>2</td>
<td>3.0</td>
<td>360</td>
</tr>
<tr>
<td>Bicycling</td>
<td>1</td>
<td>5.7</td>
<td>342</td>
</tr>
<tr>
<td>Walking</td>
<td>2</td>
<td>3.8</td>
<td>456</td>
</tr>
<tr>
<td>Lecturing etc</td>
<td>6</td>
<td>4.0</td>
<td>1440</td>
</tr>
<tr>
<td>Domestic work</td>
<td>3</td>
<td>2.0</td>
<td>360</td>
</tr>
</tbody>
</table>

These activities and non-activities require a consumption of internal energy of $\Delta U \approx 3678$ kcal.

To compensate these losses by food intake requires a daily ration of $\approx 740$ g (based on an average energy content of 5 kcal/g food).

However, choosing a Double Huddle Cheese Burger with fries takes nearly care of the daily energy needs ($\approx 2200$ kcal) after subtraction of breakfast! Dinner goes into fat storage!
Food intake in excess of the internal energy loss increases the weight of the body!

reduced food intake (diet) and/or hard work decreases the weight of the body!

EXAMPLE FOOD CONSUMPTION

The basal metabolic rate determines the energy consumption $\Delta U$ of the body ($m \approx 75$ kg) during a 10 hour night sleep!

$$\text{MBR} = 80 \text{ kcal/hr} \quad \Delta U = 800 \text{ kcal}$$

To recover the losses on internal energy, you have the choice of cereal ($\approx 300$ kcal/bowl) plus milk ($\approx 90$ kcal/bowl), or the 'healthy' version with two eggs ($\approx 80$ kcal/egg), three slices of bacon ($\approx 300$ kcal/slice) and hashbrowns ($\approx 500$ kcal).
With the first choice you replace the consumed energy from the fat reservoir of the body. Fat contains $\approx 9.3$ kcal/g, to replace 410 kcal you need to convert $\approx 44$ g of your fat storage. Your loss in body mass is $\Delta m \approx 44$ g.

With the second choice you overcompensate your losses by 760 kcal and add to the fat storage reservoir of your body. Your gain in body mass is $\Delta m \approx 82$ g.

NOTE: Because of the high energy content of fat, 9.3 kcal/g (the average energy content of food is $\approx 5$ kcal/g), the increase in fat is a very efficient way of storing energy.
DIET

means reduced food intake to convert body fat into internal energy $U$.

Taking the previous estimate of a daily consumption $\Delta U \approx 3700$ kcal, how long does a middle aged person have to be on a diet of 2000 kcal/day to reduce his body mass by 10 kg?

This translates into a daily conversion of 1700 kcal; fat contains 9.3 kcal/g

\[ \Rightarrow 10 \text{ kg} \approx 93,000 \text{ kcal} \]
\[ \Rightarrow 93000/1700 \approx 54 \text{ days} \]

Two months of fasting are required

Alternative way of loosing weight is an increase in external body activity, work $\Delta W$

Most efficient way of "working" is cycling (see next section)

How many hours of cycling are required to reduce the body mass by 10 kg?

Catabolic rate for cycling is $\Delta W / \Delta t \approx 600$ kcal/hr

\[ \Rightarrow 10 \text{ kg} \approx 93,000 \text{ kcal} \]
\[ \Rightarrow 93000/600 \approx 155 \text{ hours} \]

With 10 hrs of cycling per day a two week bike vacation is required.

Good fitness and reasonably reduced food intake are necessary!
Typical time course of weight loss during a period of constant difference between metabolic expenditure and caloric intake.

(388 kcal/day deficit)

\[ \frac{388}{9.3} = 42 \text{g of fat per day} \]

\(~1/10 \text{ lb loss per day after equilibrium is reached}~\)
Energy consumption by work

\[ \frac{\Delta W}{\Delta t} \]

≡ work rate done by external body activity

\[ \Delta W = F \cdot \Delta x \]; work ≡ force F over distance \( \Delta x \)

**EXAMPLE**  Mountain climber

lifting body against gravitational forces \( F = m \cdot g \)

average climber mass \( m = 70 \) kg
height \( \Delta h = 150 \) m

\[ \Delta W = m \cdot g \cdot \Delta h = 70 \text{ kg } 9.81 \text{ m/s}^2 \times 150 \text{ m} = 1.03 \cdot 10^5 \text{ J} \]
Person walking along a horizontal street for a distance $\Delta x = 150$ m requires less external work;

average force supplied by foot to the street $F_w \approx 0.15$ W.

$$\Delta W = F_w \cdot \Delta x = 0.15 \times 70 \, \text{kg} \times 9.81 \, \text{m/s}^2 \times 150 \, \text{m} = 1.55 \times 10^4 \, \text{J}$$

However a lot of internal force $F_L$ is necessary to lift the legs against gravitational forces (internal work)

$$\Delta W_L = F_L \cdot \Delta x_L \approx \frac{m}{7} \, \text{kg} \times 9.81 \, \text{m/s}^2 \times 0.1 \, \text{m}$$

for a $m=80$ kg person:

$$\Delta W_L = 11.2 \, \text{J}$$

net energy is not increased because dropping the leg releases potential energy

However, internal work appears as muscle heat $\Delta Q$ (not as external work $\Delta W$) and the internal work $W_L$ reduces the internal energy $U$.

The internal muscle work the body performs creates heat inside the body.
The body can be considered as a machine doing external work. This requires a conversion of $\Delta U \rightarrow \Delta W$. However, like in any other machine, no conversion is possible without any heat loss.

see ⇒ Second law of Thermodynamics

The efficiency of the machine is determined by the amount of heat loss, or by the efficiency $\varepsilon$ of the conversion.

$$
\varepsilon = \frac{\Delta W}{\Delta U} = \frac{\text{work done}}{\text{energy consumed}}
$$

The heat loss increases internal body heat or internal energy!

The efficiency for the various kind of external work depends on the detail of the muscle and body movement.

The efficiency for external work varies between 2 % and 20 %!

**Mechanical Efficiency of Man and Machines**

<table>
<thead>
<tr>
<th>Task or Machine</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycling</td>
<td>~20</td>
</tr>
<tr>
<td>Swimming (on surface)</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Swimming (underwater)</td>
<td>~4</td>
</tr>
<tr>
<td>Shoveling</td>
<td>~3</td>
</tr>
<tr>
<td>Steam engine</td>
<td>17</td>
</tr>
<tr>
<td>Gasoline engine</td>
<td>38</td>
</tr>
</tbody>
</table>
most efficient external activity is cycling: $\epsilon \approx 20\%$
The maximum power deliverance depends on its time period. For short periods of time the maximum power deliverance can be very large, e.g. bicycling and rowing $\Delta W \approx 1500$ W for $\approx 6$ s.

<table>
<thead>
<tr>
<th>Power</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>h.p.</td>
<td>watts</td>
</tr>
<tr>
<td>~2</td>
<td>~1500</td>
</tr>
<tr>
<td>~1</td>
<td>~750</td>
</tr>
<tr>
<td>~0.35</td>
<td>~260</td>
</tr>
<tr>
<td>~0.2</td>
<td>~150</td>
</tr>
<tr>
<td>~0.1</td>
<td>~75</td>
</tr>
</tbody>
</table>

For short periods the delivered power exceeds the persons maximum rate of oxygen consumption: **anaerobic phase**,

for long periods the delivered power is proportional to the rate of oxygen consumption: **aerobic phase**.