Exercise is the voluntary exertion of muscles.

**Different Types of Exercise**

Rhythmic (or dynamic) vs Isometric (or static)

Large muscle mass vs Small muscle mass

Aerobic vs Anaerobic

For patients with cardiorespiratory disease, everyday tasks may constitute maximal exercise.
Biochemistry

ATP – “The universal currency of free energy in biological systems”.

Resting muscle

[ATP] = 4mM  
[ADP] = 0.013 mM

This concentration in muscle would be sufficient to maintain contraction for < 1s.
(NB Total body content of ATP ~ 100gm, but turnover very high, a resting human consumes ~ 40 kg ATP/day).

Creatine Phosphate – A reservoir of high energy phosphoryl groups.

Resting muscle  
[creatine phosphate] = 25 mM 
[creatine] = 13 mM

Major source of ATP regeneration for a runner in first four seconds of 100 m sprint.

The fall in [ATP] of ~ 30% and [creatine phosphate] of 80% will yield 30 kJ of energy (~ 1.5 l of O₂).
**Anaerobic Metabolism**
Yields energy in absence of oxygen

![Diagram showing glycolysis process](image)

Inefficient, because only 2 – 3 ATP/glucose molecule. High power, because can have rapid throughput. Total energy yield limited by build up of lactic acidosis.

Human can produce 0.7 – 1 mol of lactate, gaining 80 – 115 kJ of energy (3.5 – 5.5 l of O\(_2\)).

Can sustain 20 – 30 s of sprinting, and explains why 200 m sprints not especially slower than 100 m sprints, unlike 400 m sprints.

85% of lactate produced is resynthesized into glycogen in the liver over the course of > 1hr – the oxygen debt.
Aerobic Metabolism

Total energy available limited only by substrate, but metabolism requires oxygen.

Efficient, because 36 – 38 ATP/glucose molecule.

Power is limited by supply of O₂.

Glycogen is stored in muscle and in liver.

Total carbohydrate store for 70 kg man is ~ 0.5 kg with the energy equivalent of 8,000 kJ.

Total fat content for 70 kg man is ~ 10.5 kg (15%) with energy equivalent 409,000 kJ.

Glycogen stores typically because depleted at some point most of the way through running a marathon. Marathon runners describe this as ‘hitting the wall’. Marathon runners will ‘carbohydrate load’ some time before the race, but near the start of race will attempt to increase fat metabolism (drinking coffee, etc).

Comparison of calorific values + respiratory quotient.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>R.Q.</th>
<th>kJ/gm</th>
<th>kJ/l O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbohydrate</td>
<td>1.00</td>
<td>17.2</td>
<td>21.1</td>
</tr>
<tr>
<td>Fat</td>
<td>~ 0.7</td>
<td>38.9</td>
<td>19.8</td>
</tr>
</tbody>
</table>

\[
\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \leftrightarrow 6\text{CO}_2 + 6\text{H}_2\text{O}.
\]

\[
\text{C}_{17}\text{H}_{35}\text{COOH} + 26\text{O}_2 \leftrightarrow 18 \text{CO}_2 + 18\text{H}_2\text{O}.
\]
Metabolic Rate/ External Work and Efficiency

O₂ consumption associated with basal metabolic rate ~ 250 ml/min O₂ consumption, (83W).

For rhythmic, dynamic exercise, can often measure external work as force * velocity.

The reciprocal of the slope of this line gives the mechanical efficiency ~ 0.20 – 0.25.

Typical passenger car petrol engine: 0.25 – 0.34.
Typical passenger car diesel engine: 0.33 – 0.40.
(figures depend on load)

Maximum oxygen uptake capacity (\(\dot{V}_{O_2}\) max) varies between individuals, and will increase with training.

For a \(\dot{V}_{O_2}\) max of 3 l/min:

Metabolic rate of 1kW, of which
200 – 250 W external work
750 – 800 W heat.
The Anaerobic Threshold

Anaerobic threshold (AT) is the $V_{O_2}$ above which lactate levels in the blood become elevated, and an oxygen debt develops.

Below AT, exercise is said to be mild/moderate. Above AT, exercise is said to be heavy.
The Oxygen Cascade

Fundamental problem is that O₂ transport has to increase by 12 fold (0.25 → 3 l/min O₂) with little increase in Pₒ₂ gradient.

Diffusion in Muscle

Muscle accounts for only ~ 20% of basal \( \dot{V}_{O₂} \), and therefore diffusion flux of O₂ across muscle has to increase ~ 60 fold.

If nothing changed, a 1mmHg diffusion gradient from capillary to mitochondrion would become a 60 mmHg diffusion gradient during exercise.

Major adaptation is capillary recruitment from 100 mm⁻² to 500 mm⁻².

This results in:
- Oxygen extraction has to rise from single capillary by 12x rather than 60x.
- On average, oxygen does not have to diffuse as far, because each capillary is only supplying 1/5 the tissue volume that a single capillary supplies at rest.

Overall effect at rest of those two factors is a 6-fold increase in diffusing capacity. Thus a 1 mm Hg gradient at rest would become a 10 mm Hg gradient in exercise.
**Oxygen Transport and Blood Flow**

Cardiac output increases by ~ 4 x, from 5 l/min at rest to 20 l/min during exercise. In order to meet the 12 x increase in $\dot{V}_{O_2}$, oxygen extraction from the blood increases by ~ 3 x, from 25% at rest to ~ 75% in exercise.

Muscle blood flow increases by a factor of ~ 20, from 25 ml min$^{-1}$ kg$^{-1}$ to ~ 500 ml min$^{-1}$ kg$^{-1}$. Since capillary number has only increased 5x, this means the transit time of blood in capillaries decreases 4 x (perhaps from 2s to 0.5 s).

A much enhanced Bohr effect (from increased CO$_2$ and H$^+$) is important to aid the unloading of twice the amount of O$_2$ in capillary in $\frac{1}{4}$ of the time.

**Oxygen Transport and the Lung**

- Pulmonary ventilation increases ~ 20-fold with maximal exercise.
- This exceeds the oxygen uptake of ~ 12-fold, and so the alveolar P$_{O_2}$ rises.
- Despite this, arterial P$_{O_2}$ may fall due to the development of a diffusion gradient associated with the increased flux of O$_2$.
- In elite athletes diffusion limitation and associated fall in arterial P$_{O_2}$ can be sufficient to cause a degree of desaturation of the arterial blood. Typically the alveolar arterial gradient may increase to 35 mmHg and arterial saturation fall to 90 mmHg. Pulmonary vascular resistance falls greatly with increased cardiac output, so that pulmonary artery pressure is only modestly raised.
The Work of the Heart

The mechanical work of the heart is increased during exercise, both because of the increase in Cardiac Output (x 4) and the increase systolic blood pressure.

The oxygen extraction of the heart is already high at rest (70%), and so the heart has to meet this demand by an increased coronary blood flow. This is done by metabolic hyperaemia.

The fraction of time in the cardiac cycle that the heart spends in diastole decreases with increasing heart rate, and so fraction of time available for myocardial perfusion decreases.

Nevertheless, coronary artery blood flow increases from 70 – 80 ml/min/100 gm at rest to 300 – 400 ml/min/100 gm.
<table>
<thead>
<tr>
<th></th>
<th><strong>Resting</strong></th>
<th><strong>Maximal</strong></th>
<th><strong>Exercise</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Healthy</td>
<td>Top Athletes</td>
<td></td>
</tr>
<tr>
<td><strong>Metabolic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total oxygen uptake</td>
<td>0.25 l/min</td>
<td>3 l/min</td>
<td>5.4 l/min</td>
</tr>
<tr>
<td><strong>Muscle</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capillary density</td>
<td>100 mm-2</td>
<td>500 mm-2</td>
<td></td>
</tr>
<tr>
<td>Oxygen uptake</td>
<td>25 ml/kg/min</td>
<td>500 ml/kg/min</td>
<td></td>
</tr>
<tr>
<td>Mitochondrial PO2</td>
<td>25 mmHg</td>
<td>1 mmHg</td>
<td></td>
</tr>
<tr>
<td><strong>Cardiovascular</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cardiac output</td>
<td>5 l/min</td>
<td>20 l/min</td>
<td>30 l/min</td>
</tr>
<tr>
<td>Heart rate</td>
<td>70 bpm</td>
<td>190 bpm</td>
<td>180 bpm</td>
</tr>
<tr>
<td>(40, top athlete)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stroke volume</td>
<td>71 ml</td>
<td>105 ml</td>
<td>167 ml</td>
</tr>
<tr>
<td>(125 ml, top athlete)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a-v O2 difference</td>
<td>5 ml/100 ml</td>
<td>15 ml/100 ml</td>
<td>18 ml/100 ml</td>
</tr>
</tbody>
</table>
Review

Following this lecture you should:

- Understand the different types of exercise that can be undertaken
- Understand the various metabolic sources of energy for undertaking exercise
- Possess a quantitative understanding of metabolic rate, external work and efficiency
- Understand the anaerobic threshold
- Understand the oxygen cascade and principal adaptations that occur in order to increase the flux of oxygen during exercise

Reading


Problem

One problem you might like to try!

A male, age 25 years, exercises at a steady-state maximum with a maximal O\textsubscript{2} uptake capacity of 4.5 l/min, an arterial content for carbon dioxide of 500 ml/l, an arterial content for oxygen of 200 ml/l, and a mixed venous carbon dioxide content of 650 ml/l. The oxygen content in his coronary sinus is measured to be 30 ml/l, and his myocardial oxygen consumption is 420 ml/min. He is working with an RQ of 0.9.

One hour later, the male is at rest with a cardiac output of 5450 ml/min, and has oxygen consumption of 273 ml/min.

1) Calculate his carbon dioxide production and cardiac output during exercise.
2) Calculate the coronary blood flow during exercise.
3) What are the energy sources of the heart during the rest?
4) Calculate the concentration of oxygen in his blood at rest, and thus the arteriovenous oxygen difference.