Chapter 5  Metabolism:
Glycolysis & Fermentation

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Office Hours: Mondays & Wednesdays 9-10 AM
Sequoia 530
Some figures taken from Krogh Biology: A Guide to the Natural World

The material presented in this lecture will be tested on Exam #2.
Exam #1 is Wednesday! Please bring a Scantron form.

Bacterial Metabolism:
3 pathways
to extract energy from glucose

- Glycolysis
- Fermentation
- Aerobic Respiration
(Krebs cycle, electron transport, oxidative phosphorylation)

Glycolysis

- Ancient metabolic pathway: 3.5 BYA…before earth’s atmosphere had oxygen in it
- The first steps of energy extraction from glucose
- Does NOT require oxygen
- Autotrophs & heterotrophs, aerobes & anaerobes all do it
- Net energy yield is small: 2 ATP per glucose

Glucose is a 6 carbon sugar

Products of glycolysis:
- Two 3-carbon molecules: pyruvic acid (x2)
- 2 reduced NADH electron carriers: from 2 NAD+
- 2 (net) ATP: from 2 ADP + 2 P

Phosphate transfers are common

Kinase: generic name for any enzyme that
adds a phosphate group to something

Phosphatase: generic name for any enzyme that
cleaves a phosphate group from something

[These are opposite activities]
Why does it take ATP to make ATP?

1. Phosphorylation of glucose “raises its energy level so it can participate in subsequent reactions (like the rock pushed out of the depression atop the hill).”

2. Phosphorylated sugars are trapped inside the cell (plain glucose freely moves in & out)

Glycolysis 2: Splitting

- 6 carbon sugar (fructose) is split into two 3-carbon molecules
- Each molecule gets one of the phosphate groups
- The molecules are not identical
- One molecule is isomerized (rearranged) so the two 3-carbon molecules become identical: glyceraldehyde 3-phosphate

Glycolysis 3: Rearrangements & energy capture

- In this series of enzyme-catalyzed reactions, energy is first extracted from the food (glucose)

★ The energy is captured in two forms:
  - NAD+ is reduced to NADH (one per 3 carbon unit)
    Carries energy as “reducing power” (more on this later)
  - ADP+Pi ➔ ATP (two per 3 carbon unit) (Substrate-level phosphorylation)
    - The inorganic phosphate (P) comes from the phosphorylated 3 carbon units

1. NAD+ reduced to NADH
2. ATP produced from ADP+Pi

End product: pyruvic acid (x2)

Carbo loading & glycolysis

- Each reaction in glycolysis is catalyzed by an enzyme
- Enzyme activity is usually regulated in some way
- Part of the reason why “Carbo loading” (eating a great deal of carbohydrates before an athletic endurance event) works may be that it induces expression of glycolytic enzymes.
  - More enzyme = faster catalytic activity = faster glycolysis

Note how the products of glycolysis (pyruvic acid, or pyruvate) are oxidized relative to the initial substrate (glucose)
### The energy balance sheet for Glycolysis

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose</td>
<td>(-2 ATP)</td>
</tr>
<tr>
<td>2 G3P</td>
<td>+2 NADH (1 per G3P) +2 ATP</td>
</tr>
<tr>
<td>2 pyruvate</td>
<td>2 ATP 2 NADH</td>
</tr>
</tbody>
</table>

**Net products of glycolysis:**
- ATP
- NADH

### Bacteria are highly diverse in their metabolic processes.

- In certain species, other pathways exist for breaking down glucose & other sugars.
  - **Bacteria can only perform a reaction if they produce the proper enzyme** (for a pathway like glycolysis, a different enzyme for each step)
  - Ability to produce an enzyme is **genetically determined** and **species-specific**

### Energy acquisition from other sugars:
- Frequently, specific enzymes are used to convert the sugar **into an intermediate of the glycolytic pathway** (one of those 3 carbon molecules...)

### What gets consumed during glycolysis?
- Glucose
- ADP + Pi
- NAD+

Without a fresh supply of these reagents, glycolysis will stop.

- **Get more:**
  - Glucose: eat something; in mammals, mobilize glycogen reserves
  - ADP: Burn energy (convert ATP to ADP + Pi)

- **??? NAD+ ???**

### Oxidation of NADH to regenerate NAD+ for glycolysis

- NADH is reduced; needs to pass off its electrons to another electron acceptor to regenerate oxidized NAD+
  - In the presence of oxygen:
    - **Electron transport chain**
    - (oxygen is the terminal electron acceptor)
  - In the absence of oxygen:
    - **Fermentation**
    - (organic terminal electron acceptors)

### Fermentation

- **Species-specific metabolic pathways for reducing pyruvic acid in the absence of oxygen**
- Some species can ferment sugars other than glucose
- End products of fermentation tell you which pathway was used

- **NADH is oxidized back to NAD+, allowing glycolysis to continue**

- Energy is **NOT captured** by **fermentation reactions**!
Homolactic acid fermentation

• Simplest pathway, one step conversion of pyruvic acid
• Only one (homo-) product: lactic acid. No gas produced

- Lactobacilli (some cheeses); streptococci; also mammalian muscle cells

\[
\begin{align*}
&\text{Reduced NAD} + H^+ &\rightarrow &\text{Oxidized NAD} \\
&\text{H}_2\text{C-C-C-OH} &\rightarrow &\text{H}_2\text{C-C-C-OH} \\
&\text{Pyruvic acid} &\rightarrow &\text{Lactic acid}
\end{align*}
\]

Alcoholic Fermentation

- 2 steps; CO₂ gas & ethyl alcohol are products
- Rare in bacteria, common in yeast
- Bread & wine

\[
\begin{align*}
&\text{Pyruvic acid} &\rightarrow &\text{CO}_2 + \text{H}_2\text{C-C-H} \\
&\text{H}_2\text{C-C-C-OH} &\rightarrow &\text{Acetaldehyde} \\
&\text{Carbon dioxide} &\rightarrow &\text{H}_2\text{C-C-H} \\
&\text{Lactobacilli} &\rightarrow &\text{Ethyl alcohol}
\end{align*}
\]

Other fermentation pathways

- Performed by a great variety of microbes
- We’ll test for many pathways in lab
  - generally by looking for end products or intermediates
- A huge range of products can be produced
- Many have commercial utility; others are involved in disease, food spoilage, etc.

Terminal electron acceptors

• The goal of fermentation is to oxidize NADH
• Something must be reduced (the electrons must go somewhere)
• Organic compounds (for example, lactic acid & ethyl alcohol) are the terminal electron acceptors in fermentation pathways

Later: how using OXYGEN as the terminal electron acceptor is a MUCH better deal!!!