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Chapter 8: Cellular Respiration

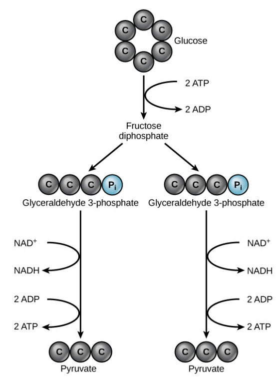
Glycolysis

❖ 8.1 Introduction

$C_6H_{12}O_6 + 6O_2 \Rightarrow 6CO_2 + 6H_20 + ATP$
Glucose Oxygen Carbon Dioxide Water Energy

- ➢ Glycolysis - the first step in the breakdown of glucose; process of breaking glucose into two three-carbon molecules with the production of ATP and NADH; **ana**erobic
  - ■ **Ana**erobic - process that does not use oxygen
  - ■ Glycolysis takes place in the cytosol
- ➢ Pyruvate - three-carbon sugar that can be decarboxylated and oxidized to make acetyl CoA, which enters the citric acid cycle under **aer**obic conditions; the end product of glycolysis
- ➢ There are 2 pathways in glucose catabolism—*glycolysis* and *Citric Acid/Krebs Cycle*—generate ATP
- ➢ 3 Sequential Pathways: *glycolysis*, *Citric Acid/Krebs Cycle*, and *Electron Transfer Phosphorylation*

❖ 8.1a: Steps of Glycolysis



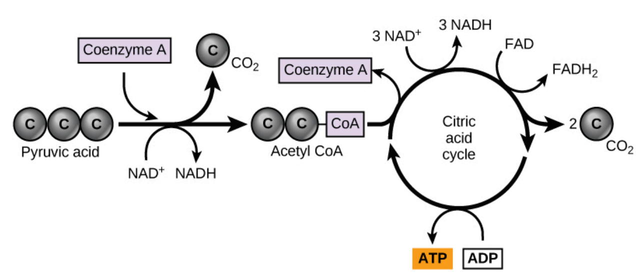
- ➢ Step 1: phosphorylation of glucose by hexokinase
  - ■ Add a phosphate group to glucose, producing glucose-6-phosphate (G6P)
    - ● Ensures that the concentration gradient of glucose remains unchanged
  - ■ Convert G6P into fructose diphosphate through the addition of a second phosphate group
    - ● The phosphates come from ATP
    - ● To convert glucose to fructose diphosphate, the cell must break a phosphate from 2 ATPs (makes them ADPs)
- ➢ Step 2: split fructose diphosphate into two molecules of glyceraldehyde 3-phosphate (G3P)
- ➢ Step 3: convert G3P to pyruvate
  - ■ Add another phosphate group (not from ATP) to G3P
    - ● Reduces 2 NAD^+ to 2 NADH by adding 2 electrons and a proton to each
    - ● At this point, the two phosphates that are on each molecule are removed, and added back to ADP molecules, generating 4 ATP molecules, and 2 pyruvate molecules

❖ 8.1b: Outcomes of Glycolysis

- ➢ Starts with glucose and ends with 2 pyruvate molecules, 4 ATP, amd 2 NADH
  - ■ Two ATP molecules were used in the first half of the pathway to prepare the six-carbon ring for cleavage, so the cell has a net gain of two ATP molecules and 2 NADH molecules for its use
- ➢ If the cell cannot catabolize the pyruvate molecules further, it will harvest only two ATP molecules from one molecule of glucose
- ➢ **Aer**obic Respiration - process in which organisms convert energy in the presence of oxygen
  - ■ Cannot be done by mature mammalian red blood cells; only some bacteria

Citric Acid/Krebs Cycle and Oxidative Phosphorylation

❖ 8.2a: The Citric Acid/Krebs Cycle - a series of enzyme-catalyzed chemical reactions of central importance in all living cells that harvests the energy in carbon-carbon bonds of sugar molecules to generate ATP; the citric acid cycle is an **aer**obic metabolic pathway because it requires oxygen in later reactions to proceed



- ➢ Pre-Citric Acid/Krebs Cycle Step: Conversion of Pyruvate to Acetyl CoA
  - ■ Pyruvate (3-C atom) becomes an acetyl group that attaches to Coenzyme A
    - ● Purpose of CoA is to shuttle the pyruvate to mitochondria from the cytosol
    - ● Creates acetyl CoA (2-C atom because on splits off to form CO_2)

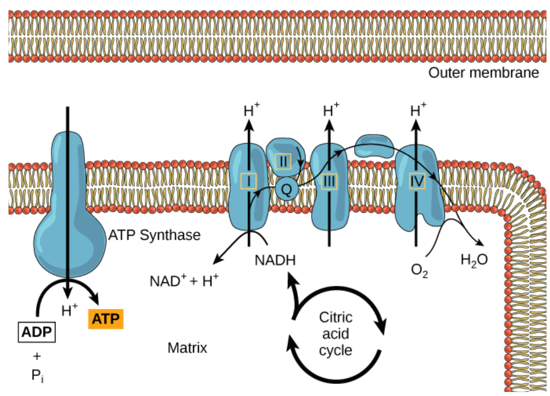
Name: ___________________

- The acetyl group begins the Citric Acid/Krebs Cycle

- ➢ Citric Acid/Krebs Cycle
  - ■ Overview
    - Still takes place in mitochondrial matrix
    - Citric Acid/Krebs Cycle is a *closed loop* as opposed to glycolysis
      - ◆ The last part of the pathway regenerates the compound used in the first step
  - ■ The 8-Reaction Process
    - Produces 2 carbon dioxide molecules, 1 ATP molecule (or an equivalent), and reduced forms (NADH and $FADH_2$) of NAD^+ and FAD^+
      - ◆ Acetyl group comes from the pyruvate and becomes CO_2
      - ◆ The NAD+ is *reduced* to high-energy NADH
      - ◆ ADP + P combines into ATP
      - ◆ FAD is *reduced* to high-energy $FADH_2$
        - ➢ NAD+ and FAD are the *oxidized* forms of NADH and $FADH_2$
    - Takes 2 turns of the cycle to make a single glucose molecule
    - 1 ATP is made with each turn

Citric Acid/Krebs Cycle	
Input	*Output*
Acetyl Group	2x CO_2
3x NAD+	3x NADH
ADP + P	ATP
FAD	$FADH_2$

- ❖ 8.2b: Oxidative/Electron Transport Phosphorylation/Chemiosmosis - ATP is produced by passing electrons through the ETC; that energy moves H+ to create a proton gradient that forces H+ through ATP synthase
  - ➢ Most ATP that is generated during aerobic catabolism of glucose comes from this
    - ■ Begins with passing electrons through a series of chemical reactions to a final electron acceptor, oxygen
    - ■ Reactions take place in specialized protein complexes in the mitochondria of eukaryotes; inner part of the prokaryotic cell membrane
  - ➢ The ETC is the last part of aerobic respiration; only part of the metabolism to use atmospheric oxygen
  - ➢ Electron Transport Chain (ETC) - a series of four large, multi-protein complexes embedded in the inner mitochondrial membrane that accepts electrons from donor compounds and harvests energy from a series of chemical reactions to generate a hydrogen ion gradient across the membrane (shown right)



    - ■ Resembles a bucket brigade; electrons are passed rapidly from one component to the next, to the endpoint of the chain where *oxygen is the final electron acceptor*; water is produced
    - ■ There are 4 protein complexes labeled I-IV
      - Aggregation of these, together with associated mobile (accessory electron carriers) makes up the ETC
    - ■ The Process
      - ETC collects e^- from NADH and $FADH_2$ and oxidizes them (NAD+ and FAD
      - The e^- (with elevated energy from PSI) are used to create the proton gradient
      - Leftover e^- would destroy the cell's DNA if not for O_2
        - ◆ **$4e^- + 4H + O_2 \rightarrow H_2O$** (last reaction of ETC)
- ❖ 8.2c: ATP Yield
  - ➢ The amount of ATP that can be generated from glucose depends on multiple factors
    - ■ Number of hydrogen ions that the electron transport chain complexes can pump through the membrane varies between species
    - ■ Shuttling of electrons across the mitochondrial membrane
      - The NADH generated from glycolysis cannot easily enter mitochondria
      - So, electrons are picked up on the inside of the mitochondria by either NAD + or FAD +
      - Fewer ATP molecules are generated when FAD + acts as a carrier

- NAD + is used as the electron transporter in the liver and FAD + in the brain, so ATP yield depends on the tissue being considered
- intermediate compounds in these pathways are used for other purposes
  - Glucose catabolism connects with the pathways that build or break down all other biochemical compounds in cells
  - Results in something somewhat messier than the ideal situations for making ATP

➢ Overall, in living systems, these pathways of glucose catabolism extract about 34 percent of the energy contained in glucose

Metabolism and Oxygen

❖ 8.3 Introduction

➢ In **aer**obic respiration, the final electron acceptor is an oxygen molecule, O_2

- If aerobic respiration occurs, then ATP will be produced using the energy of high-energy electrons carried by NADH or $FADH_2$ to the electron transport chain
- If aerobic respiration does not occur, NADH must be reoxidized to NAD^+ for reuse as an electron carrier for the glycolytic pathway to continue
  - Done by using an organic molecule as the final acceptor without an ETC
- Fermentation - process of regenerating NAD^+ with either an inorganic or organic compound serving as the final electron acceptor, occurs in the absence; occurs in the absence of oxygen
  - **Ana**erobic Cellular Respiration - process in which organisms convert energy for their use in the absence of oxygen

❖ 8.3a: **Ana**erobic Cellular Respiration

➢ Certain prokaryotes (some bacteria species and Archaea) use anaerobic respiration

❖ 8.3b: Fermentation

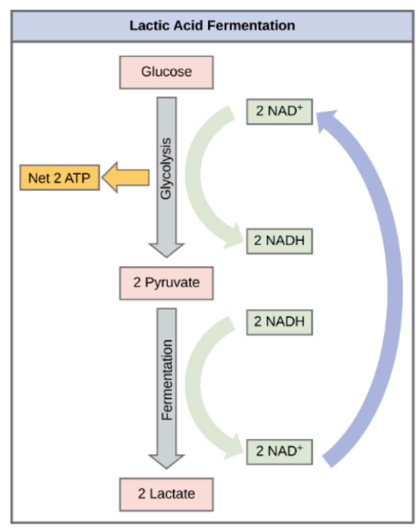
➢ Yeast

- e- are transformed into pyruvate
- Carbon form the pyruvate is taken care of; converted into CO_2 (2-C) and ethanol (2-C)

➢ All forms of fermentation, except lactic acid fermentation, produce gas

➢ The type used by animals and certain bacteria is *lactic acid fermentation*

- Used routinely in mammalian red blood cells and in skeletal muscle that has an insufficient oxygen supply to allow aerobic respiration to continue
- When lactic acid depornates (releases H^+ and changes to lactate)
- The excess lactate must be removed by blood circulation
- Lactate is brought to the liver for further metabolism, converted back to pyruvate
- Chemical Reaction
  - **Pyruvate + NADH ↔ lactic acid + NAD^+ ↔ lactate + H^+**
- Reaction can proceed in either direction, but left to right is inhibited by acidic conditions



Lactic acid fermentation is common in muscle cells that have run out of oxygen.

➢ Alcoholic Fermentation

- Produces ethanol
- Chemical Reaction
  - **Pyruvate → CO_2 + acetaldehyde + NADH → ethanol + NAD^+**
- First reaction
  - Catalyzed by pyruvate decarboxylase, a cytoplasmic enzyme, with a coenzyme of thiamine pyrophosphate (TPP, derived from vitamin B_1 and also called thiamine)
  - A carboxyl group is removed from pyruvic acid, releasing carbon dioxide as a gas

            - The loss of carbon dioxide reduces the size of the molecule by one carbon, making acetaldehyde
        - Second Reaction
            - Catalyzed by alcohol dehydrogenase to oxidize NADH to NAD^+ and reduce acetaldehyde to ethanol
    - Other Types of Fermentation
        - Occurs in bacteria
        - Many prokaryotes are facultatively **ana**erobic (having the ability to switch between aerobic respiration and fermentation, depending on the availability of oxygen)
        - Others are obligate **ana**erobes (having the ability to live and grow in the absence of molecular oxygen)
            - Oxygen is poisonous to them and kills on exposure
        - Various methods of fermentation are used by assorted organisms to ensure an adequate supply of NAD^+ for the sixth step in glycolysis
        - Without these pathways, that step would not occur and no ATP would be harvested from the breakdown of glucose
    - The production of particular types of gas is used as an indicator of the fermentation of specific carbohydrates, which plays a role in the laboratory identification of the bacteria
- 8.4b: Slow and Fast Twitch
    - Red Muscles/Slow Twitch
        - Cells have abundant mitochondria and myoglobin (protein that stores oxygen in a stockpile)
        - Cells gradually generates ATP very efficiently through cellular respiration
        - Distance runner
    - White Muscle/Fast Twitch
        - Cells have little to no mitochondria and myoglobin
        - Cells rapidly generate ATP via lactic acid fermentation
        - Sprint runner
    - You have a mixture of both slow and fast along with intermediate twitch muscles