**Cellular Respiration Notes 2019**

**Concept: Catabolic pathways yield energy by oxidizing organic fuels**

Energy is stored in organic molecules such as carbohydrates, fats, proteins

-Heterotrophs eat these organic molecules 🡪 food. Food is digested into organic molecules to get… raw materials for synthesis, fuels for energy.

Glucose is the model for breakdown into useable energy, \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ of glucose to produce ATP

Digest large molecules into smaller ones. This is by breaking bonds & moving electrons from one molecule to another. As electrons move they “carry energy” with them. That energy is stored in another \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_, released as heat or harvested to make ATP.

Catabolic pathways occur when molecules are broken down and their energy is released. Two catabolic pathways to know:

-Fermentation: the partial degradation of sugars that occur without the use of oxygen

-Aerobic respiration: the most prevalent and efficient pathway in which oxygen is consumed as a reactant along with the organic fuel.

Carbohydrates, fats and proteins can all be broken down to release energy in cellular respiration. However, glucose is the primary molecule that is used in cellular respiration. The standard way of representing the process of cellular respiration shows glucose being broken down in the following reaction:

C6H12O6 + 6O2 🡪 6CO2 + 6H20+ Energy (686 kcal/mol of glucose).

Electrons cannot move alone in cells. Electrons move as part of H atom. When you move H = move electrons

Energy is release as breakdown organic molecules by breaking C-C bonds.

-strip off electrons from C-H bonds by removing H atoms (C6H12O6 🡪 CO2 = the fuel has been \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_).

-Electrons attracted to more electronegative atoms. In biology, the most electronegative atom? Oxygen: O2 🡪 H2O = oxygen has been \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

couple REDOX (oxidation-reduction) reactions & use the released energy to synthesize \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Oxidation adds oxygen, removes hydrogen, loses electrons, releases energy, and is \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Reduction removes oxygen, adds hydrogen, gains electrons, stores energy, and is endergonic

Moving electrons in respiration by electron carriers. Use H atoms to move electrons around.

-NAD+ 🡪 NADH (reduced)

-FAD+2 🡪 FADH2 (reduced)

**Concept: Glycolysis harvests chemical energy by oxidizing glucose to pyruvate**

Glycolysis

Breaking down glucose: “glyco – lysis” (splitting sugar)

-ancient pathway which harvests energy

-where energy transfer first evolved

-transfer energy from organic molecules to ATP

-still is starting point for ALL cellular respiration

-but it’s inefficient; generate only \_\_\_\_\_\_\_\_ ATP for every 1 glucose and occurs in cytosol

-Evolutionary Perspective

-Prokaryotes: first cells had no organelles

-Anaerobic atmosphere:

-life on Earth first evolved without free \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ (O2) in atmosphere

-energy had to be captured from organic molecules in absence of O2

-Prokaryotes that evolved glycolysis are ancestors of all modern life. \_\_\_\_\_\_\_\_\_\_\_ cells still utilize glycolysis

-Overview of Glycolysis:

-10 reactions

-convert \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ (6C) to 2 pyruvate (3C)

-produces: 4 ATP & 2 NADH

-consumes: \_\_\_\_\_\_\_\_\_ ATP

-net yield: 2 ATP & 2 NADH

 -Endergonic: Invest some ATP (2)

 -Exergonic: Harvest a little ATP and a little NADH

 -Net yield: 2 ATP and 2 NADH

1st Half of Glycolysis (5 reactions)

 -Glucose “priming”

 -get glucose ready to split by phosphorylation, molecular rearrangement

 -Split destabilized glucose molecule

2nd Half of Glycolysis (5 reactions)

 -Energy Harvest

 -NADH production

 -G3P donates H

 -oxidizes the sugar

 -reduces NAD+

 -NAD+ 🡪 \_\_\_\_\_\_\_\_\_\_\_\_\_\_

 -ATP production

 -G3P 🡪 🡪 🡪 pyruvate

 -PEP sugar donates P

 -substrate level phosphorylation

 -ADP 🡪 \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

 - In the last steps of glycolysis, where did the P come from to make ATP?

-the sugar substrate (PEP)

Is that all there is?

 Not a lot of energy…for 1 billon years+ this is how life on Earth survived

There was no O2 = slow growth, slow reproduction

-only harvest 3.5% of energy stored in glucose

-more carbons to strip off = more energy to harvest

But Can’t stop there! Raw materials 🡪 products

 -glucose + 2ADP + 2Pi + 2NAD+ 🡪 2 pyruvate +2ATP +2NADH

 - Going to run out of NAD+ without regenerating NAD+, energy production would \_\_\_\_\_\_\_\_\_!

-another molecule must accept H from NADH, so NAD+ is freed up for another round

**Concept: Fermentation and anaerobic respiration enable cells to produce ATP without the use of oxygen**

How is NADH recycled back to NAD+?

 -Another molecule must accept H from NADH. The H acceptor depends on if oxygen is available. If oxygen is available (\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ respiration), then oxygen will accept H to form water. Without oxygen (\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ respiration) “fermentation” occurs. Fermentation can be with the production of lactic acid or alcohol. This process of fermentation recycles NADH to NAD+.

**Anaerobic fermentation**

-Bacteria and yeast (beer, wine, bread) use alcoholic fermentation to make NADH 🡪 NAD+

-Pyruvate 🡪ethanol +CO2

-Dead end process: at approx. 12% ethanol kills yeast. Not reversible.

-Animals and some fungi use lactic acid fermentation (cheese, anaerobic exercise (no O2) to make NADH 🡪 NAD+.

-Pyruvate 🡪 lactic acid

 -Reversible process once O2 is available, lactate is converted back to pyruvate by the \_\_\_\_\_\_\_\_.

Pyruvate is a branching point: Oxygen or No Oxygen. If oxygen is available, pyruvate moves onto the mitochondria (aerobic respiration). If no oxygen is available, fermentation occurs in the cytosol (cytoplasm). Anaerobic respiration.

Glycolysis is only the start: Glucose (6 carbon is split into two molecules each 3 carbon)

-Pyruvate has more energy to yield by taking 3 more C to strip off (to \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_)

-if O2 is available, pyruvate enters mitochondria

-enzymes of Krebs cycle complete the full oxidation of sugar to CO2

-Pyruvate is broken down into CO2 (which has 1 carbon)

Mitochondria-Structure

Double membrane energy harvesting organelle with a smooth outer membrane and a highly folded inner membrane (\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_). There is intermembrane space with fluid-filled space between membranes. The inner fluid-filled space is called the matrix. It has DNA, ribosomes, and enzymes which are free in matrix and membrane-bound space.

Mitochondria-Function

Dividing mitochondria: Who else divides like that? Bacteria. Remember the endosymbiosis theory!

Membrane-bound proteins make enzymes and permeases (membrane transport proteins). The advantage of highly folded inner membrane is that there is more \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ area for membrane bound enzymes and permeases.

**Concept: After pyruvate is oxidized, the citric acid cycle completes the energy yielding oxidation of organic molecules**

Oxidation of pyruvate

 -2 Pyruvate enters mitochondrial matrix each with 3 carbons. They are oxidized to produce 2 acetyl CoA. There are 3 steps to oxidize pyruvate. The oxidation releases 2 CO2, releases 2 NAD, produces 2 acetyl-CoA (2 carbon molecules each). Acetyl CoA enters \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ cycle.

Krebs Cycle (Citric Acid Cycle)

 -occurs in the mitochondrial \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

 -8 steps: each catalyzed by specific enzyme. Catabolism of 6C citrate molecule

Evolved later than glycolysis

 -does that make evolutionary sense?

 -bacteria 🡪 3.5 billion years ago (glycolysis)

 -free O2 🡪 2.7 billion years ago (photosynthesis)

 -eukaryotes 🡪 1.5 billion years ago (aerobic respiration = organelles 🡪 mitochondria)

Each (3 carbon) pyruvate is broken down into (2 carbon) acetyl CoA. Acetyl CoA binds with a 4 carbon molecule and makes a 6 carbon citrate molecule. Carbons are oxidized to make 2 CO2 molecules. Leaving a 4 carbon molecule which will be modified back to the first 4 carbon molecule which binds with another acetyl CoA.

Each pyruvate is oxidized to provide 4 NADH electron carriers (1 from breakdown of pyruvate to acetyl CoA, 3 from Krebs) and 1 FADH2 molecules. So, when 1 glucose is fully oxidized \_\_\_\_\_\_\_\_\_\_ ATP are directly produced (2 from glycolysis and 2 from Krebs).

Electron Carriers = Hydrogen Carriers

 -Krebs cycle produces large quantities of electron carriers (NADH and FADH2). The electron carriers go to the Electron Transport \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_. Net gain = 2 ATP and 8 NADH + 2 FADH2

Value of Krebs cycle?

 - If the yield is only 2 ATP then how was the Krebs cycle an adaptation? The value of NADH & FADH2 as electron carriers & H carriers is much more important. NADH and FADH2 molecules move electrons/ H+ ions

Electron Transport Chain is a series of proteins built into inner mitochondrial membrane along \_\_\_\_\_\_\_\_\_\_\_\_\_

which transport proteins & enzymes.

The electron transport chain transport of electrons down ETC linked to pumping of H+ to create H+ gradient

yields ~\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ ATP from 1 glucose! Only in presence of O2 (aerobic respiration)

Electron Carriers from Glucose: 2 NADH from glycolysis, 2 NADH from 2 Pyruvate🡪 2 Acetyl CoA breakdown, 6 from Krebs cycle. Total 10 NADH and 2 FADH2 are produced.

Electron Transport Chain:

NADH 🡪 NAD+ + H. Each H is made of a proton + and an electron (-). The protons are pumped through proteins in the membrane (NADH dehydrogenase, cytochrome bc complex, cytochrome c oxidase complex). What powers the proton pumps? \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_!!!!! From the hydrogen atoms.

Electron carriers pass electrons & H+ to ETC

-H cleaved off NADH & FADH2

-electrons stripped from H atoms 🡪 H+ (protons)

-electrons passed from one electron carrier to next in mitochondrial membrane (ETC)

-flowing electrons = energy to do work

-transport proteins in membrane pump H+ (protons) across inner membrane to intermembrane space

What pulls the electrons down the ETC? Oxygen!!!!

-Electrons move in steps from carrier to carrier downhill to oxygen

-each carrier more electronegative

-controlled oxidation

-controlled release of energy

With H protons pumped into the intermembrane space, it creates a H+ gradient. Allows the protons to flow through ATP synthase. As H + protons funnel through the ATP synthase complex, ADP + Pi 🡪 ATP

**Concept: During Oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis**

Chemiosmosis

The diffusion of \_\_\_\_\_\_\_\_\_\_\_\_\_\_ across a membrane. This allows the build up of proton gradient just so H+ could flow through ATP synthase enzyme to build ATP

Step 1: Electrons are harvested and carried to the transport system (NADH)

Step 2: Electrons provide energy to pump protons across the membrane

Step 3: Oxygen joins with protons to form water

Step 4: Protons diffuse back in down their concentration gradient, driving the synthesis of ATP

The electron transport chain and chemiosmosis make up oxidative phosphorylation. This specific term is used because ADP is phosphorylated and oxygen is necessary to keep the electrons flowing.

Substrate level phosphorylation occurs when an enzyme, a kinase, transfers a phosphate from a substrate directly to ADP. Only a small amount of ATP is produced this way. This is the way energy is produced during glycolysis and the Krebs cycle.

Where did the glucose come from?

Where did the O2 come from?

Where did the CO2 come from?

Where did the CO2 go?

Where did the H2O come from?

Where did the ATP come from?

What else is produced that is not listed in this equation?

Why do we breathe?

Why is the ETC and Krebs cycle considered aerobic? What happens if oxygen is not available?

 ETC backs up as there is nothing to pull electrons down chain

-NADH & FADH2 can’t unload H

-ATP production ceases

-cells run out of energy and you die!

Beyond glucose: Other carbohydrates:

Glycolysis accepts a wide range of carbohydrates fuels. Polysaccharides are hydrolyzed into glucose. Other 6C sugars (fructose, galactose) are modified into glucose.

Proteins are hydrolyzed into amino acids.

Fats are hydrolyzed into glycerol and fatty acids. Fat generates 2x ATP vs carbohydrates. There is more C in a gram of fat, more energy in releasing bonds. More O in a gram on carbohydrate, so it is already partly oxidized needing less energy to release.

Coordination of chemical processes across whole organism through digestion (catabolism when organism needs energy or needs raw materials) and synthesis (anabolism when organism has enough energy & a supply of raw materials) and by regulating enzymes including feedback mechanisms. Raw materials stimulate production and products inhibit further production

**Concept: Glycolysis and the citric acid cycle connect to many other metabolic pathways**

Metabolism:

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ of carbohydrates, fats & protein are all catabolized through same pathways but enter at different points. The cell extracts energy from every source

Synthesis is dependent on having enough energy? build stuff! The cell uses points in glycolysis & Krebs cycle as links to pathways for synthesis. It run pathways “backwards” to have extra fuel, build fat!

Regulation of Cellular Respiration:

There are control points to regulate cellular respiration. Phosphofructokinase (PFK) is an allosteric enzyme that functions early in the pathway of glycolysis and acts as a regulator of respiration. It is inhibited by high levels of ATP, which stops the catalytic pathway of glycolysis.

Basic principles of supply & demand regulate metabolic economy

There is a balance the supply of raw materials with the products produced

-these molecules become feedback regulators

-they control:

-enzymes at strategic points in glycolysis & Krebs cycle

-levels of AMP, ADP, ATP

-regulation by final products & raw materials

-levels of intermediates compounds in pathways

-regulation of earlier steps in pathways

-levels of other biomolecules in body

-regulates rate of siphoning off to synthesis pathways