

Cellular Respiration Notes 2024

Concept: Catabolic pathways yield energy by oxidizing organic fuels

Harvesting Stored Energy

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

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

Harvesting Stored Energy

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

How do we harvest energy from fuels?

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.

Two Types of Catabolic Pathways

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:

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{Energy (686 kcal/mol of glucose)}.$

How do we move electrons in biology?

-Moving electrons in living systems

-Electrons cannot move alone in cells. Electrons move as part of H _____.

-When you move H = _____ electrons

Coupling oxidation and reduction

-REDOX reactions in respiration

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

-strip off electrons from C-H bonds by removing H atoms ($C_6H_{12}O_6 \rightarrow CO_2$ = the fuel has been _____).

-Electrons attracted to more electronegative atoms. In biology, the most electronegative atom?

Oxygen: $O_2 \rightarrow H_2O$ = oxygen has been _____

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

Oxidation and Reduction

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:

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

- NAD⁺ → NADH (reduced)
- FAD+2 → FADH₂ (reduced)

Overview of cellular respiration

4 metabolic stages:

- Anaerobic respiration
 - Glycolysis: respiration without oxygen which occurs in the cytosol
- Aerobic respiration
 - respiration using oxygen and occurs in the mitochondria
 - Pyruvate oxidation, Krebs Cycle, and Electron Transport Chain

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 billion 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 + 2P_i + 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 CO_2
- Pyruvate is broken down into CO_2 (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 CO_2 , 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 $\approx$ 3.5 billion years ago (glycolysis)
 - free O_2 $\approx$ 2.7 billion years ago (photosynthesis)
 - eukaryotes $\approx$ 1.5 billion years ago (aerobic respiration = organelles $\approx$ 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 CO_2 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 FADH_2 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 FADH_2). The electron carriers go to the Electron Transport _____. Net gain = 2 ATP and 8 NADH + 2 FADH_2

Value of Krebs cycle?

- If the yield is only 2 ATP then how was the Krebs cycle an adaptation? The value of NADH & FADH_2 as electron carriers & H carriers is much more important. NADH and FADH_2 molecules move electrons/ H^+ ions
- NADH and FADH_2 are to be used in the Electron Transport Chain

There is a better way!

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 O_2 (_____ 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.

Stripping H from Electron Carriers

Electron carriers pass electrons & H^+ to ETC

- H cleaved off NADH & FADH₂

- _____ 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 flow downhill

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

- each carrier more electronegative

- controlled oxidation

- controlled release of energy

We did it!

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

- Each NADH can produce up to _____ ATP

- Each FADH₂ can produce up to _____ 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?

Taking it beyond....

What is the final electron acceptor in the Electron Transport Chain? – Oxygen

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.

Beyond glucose: proteins

Proteins are hydrolyzed into amino acids.

Beyond glucose: fats

Fats are hydrolyzed into glycerol and fatty acids. Fat generates 2x _____ 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.

Metabolism

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

Metabolism

_____ is dependent on having enough energy? _____ 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!