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Cell Respiration Steps

- cellular respiration: the creation of usable energy to do cellular work from stored chemical energy (breaking down of glucose and creating of ATP (adenosine triphosphate, the high-energy molecule that our body can use directly as energy)), which occurs in three stages (sometimes only one takes place)
    - anaerobic respiration: glycolysis
        - does not require oxygen to happen, but still creates a little energy (but not enough for larger organisms, such as us)
        - happens in all cells (only stage that does)
            - only step in cells in non-oxygen environments (e.g. anaerobic bacteria)
            - only step in cells without a mitochondria (e.g. protists); happens in cytoplasm
            - in cells with mitochondria, used to provide NADH for oxidative phosphorylation
        - glucose + 2 ADP + 2 P_i → 4 ATP (+ pyruvate + 2 H_2O)
    - aerobic respiration: Krebs cycle and oxidative phosphorylation
        - take place in mitochondrial matrix and on mitochondrial inner membrane (on cristae: folds) require oxygen as final electron acceptor so that electrons can pass through
        - cells in eukaryotic cells with a mitochondrial (mostly plant and animal cells)
        - Krebs, like glycolysis, to provide high-energy electrons for oxidative phosphorylation
        - happens more in more active cells, such as muscle cells, liver and intestinal and nerve cells (secretions = bulk transport = ATP)
        - glucose + 30-32 ADP + 30-32 P_i → 30-32 ATP (+ 6 CO_2 + 14 H_2O)
            - only stores 34% of glucose's potential energy (but still more efficient than gasoline or other artificial fuels)
- cellular work: any process in a cell that requires the cell to expend energy in the form of ATP
    - membrane transport
    - cellular division
    - enzymes (chemical reactions)
    - contractile/motor proteins
    - change shape of cell (changing cytoskeleton)
    - making proteins
    - flagella, cilia
- calorimetry: the science of the amount of energy stored in a substance
    - can use a (soda-can) calorimeter and burn the substance (combustion reaction to release heat and light energy from chemical energy reacting with oxygen) to see how much it heats up the liquid in the can— the more the heat increase, the more the calories
    - 1 calorie = amount of energy needed to heat up 1 gram of water by 1 degree Celsius
    - 1 Calorie = 1 kilocalorie
- "-ate" molecules: salt/ionized form of "-ic acid"
    - pyruvate → ionized pyruvic acid
    - citrate → ionized citric acid
    - oxaloacetate → ionized oxaloacetic acid
- intermediate (molecule): molecule that is formed between the reactant and the product of a metabolic pathway (a chain of chemical reactions that turns the reactant into intermediates to arrive at the product)
    - glycolysis:
        - glucose 6-phosphate
        - glucose 1,6-phosphate
        - fructose 1,6-phosphate
        - glyceraldehyde 3-phosphate

        - dihydroxyacetone phosphate
        - 1,3-bisphosphoglycerate
        - 3-phosphoglycerate
        - phosphoenol-pyruvate
    - Krebs:
        - oxaloacetate
        - citrate
        - alpha-ketoglutarate
        - succinate
        - malate
    - oxidative phosphorylation:
        - (none— not a metabolic pathway)
- poisons: substances that bind to and block the ETC in oxidative phosphorylation, stopping the creation of ATP and killing the cell within minutes
    - rotenone blocks first protein complex
    - cyanide, carbon monoxide block third protein complex
    - oligomycin blocks ATP synthetase
    - DNP is an uncoupling agent (see thermogenin under brown fat)
- brown fat: fat tissue that has a high capillary and mitochondrial content that creates less ATP but creates more heat
    - used during hibernation— need to stay warm but don't need to create much ATP
    - high concentration in newborns to stay warm— lose it as we get older
    - uncoupling protein thermogenin in the inner mitochondrial membrane that causes protons to fall back into the matrix before they form ATP, creating heat instead of ATP
- end of reactants:
    - glucose → 6 CO_2 + 12 H_2O (from NADPH)
    - oxygen → 12 H_2O
- fermentation: glycolysis without oxygen (must have method of recycling NADH)
    - lactic acid fermentation:
        - pyruvate is turned into lactic acid and NADH is oxidized to NAD^+
        - in bacteria
        - in our muscle cells
            - lactic acid flows into our bloodstream, is turned back into pyruvate in the liver and the rest of cellular respiration takes place
    - alcohol fermentation
        - pyruvate is turned into CO_2 and ethanol, and NADH is oxidized to NAD^+
        - in yeast and certain bacteria
        - used in winemaking
- types of organisms (based on oxygen)
    - aerobe can only survive in oxygen environments
    - facultative anaerobe can survive by either fermentation (no-oxygen) or oxidative phosphorylation (with oxygen), but prefers oxygen
    - obligate anaerobe is poisoned by oxygen, must live in non-oxygen environment
- glucose not the starting material
    - carbohydrates can all be broken down (polymers) or turned into (monomers) glucose to start cell respiration

- fats can be broken down into glycerol and fatty acids, which can both be used in cell respiration (turned into G3P and acetyl CoA, respectively) and produce 9/4 times the energy of glucose (has many hydrogens and high-energy electrons)
- proteins can be broken down into amino acids (turned to various intermediates) and amino groups (which are waste products and disposed of in the urine)

- biosynthesis
  - glycolysis and Krebs cycle also create intermediates that can be used to form new macromolecules

Molecule / Step	**Description**
glucose	
1. Glycolysis	takes place in cell cytoplasm happens in all cells (can happen without oxygen, is the only step in anaerobic or prokaryotic cells) $2\ ATP + 2\ P_i + 2\ NAD^+ + glucose \rightarrow 4\ ATP + 2\ NADH + 2\ pyruvate$
$+P_i$	ATP phosphorylates it (1 phosphate group is fixed, ADP leaves into cytoplasm)
glucose 6-phosphate	
$+P_i$	ATP phosphorylates it (1 phosphate group is fixed, ADP leaves into cytoplasm)
glucose 1,6-phosphate	
fructose 1,6-phosphate	
hydrolysis	fructose 1,6-phosphate is unstable, causes breakdown into two two-carbon sugars
glyceraldehyde 3-phosphate (G3P) + dihydroxyacetone phosphate	high-energy sugar, also found as product of Calvin Cycle in photosynthesis + secondary, three carbon sugar
2 glyceraldehyde 3-phosphate	dihydroxyacetone phosphate is turned into a G3P molecule
	All following steps (including in other stages of cellular respiration) will be halved for convenience. Each reaction following takes place on *each* G3P.
$-2e^- -H^+$	reduces NAD^+ electron carrier ($NAD^+ \rightarrow NADH$); NADH carries high-energy electrons to mitochondrial membrane, and drops it off to protein carriers; from there, it may be dropped off either into FAD or NAD^+, so that will cause the differences in the amounts of ATP produced
$+P_i$	ATP phosphorylates it because it is now positive after removing electrons (1 phosphate group is fixed, ADP leaves into cytoplasm); can be used immediately

1,3-bisphosphoglycerate	
-P_i	substrate-level phosphorylation: ATP is synthesized by phosphorylating ADP with P_i from substrate molecule (substrate is molecule bonded to enzyme; as opposed to oxidative phosphorylation, when electrons power phosphorylation); can be used immediately; in organisms in anaerobic environments or ones without mitochondria, this is all the ATP they will have to work (very little)
3-phosphoglycerate (3PGA)	low-energy 3-carbon sugar
-H_2O	
phosphoenol-pyruvate	
-P_i	substrate-level phosphorylation: ATP is synthesized by phosphorylating ADP with P_i from substrate molecule (as opposed to oxidative phosphorylation)
pyruvate	final product of glycolysis; carried across mitochondrial membrane by protein carrier into the matrix of the mitochondria
2a. Pre-Krebs	takes place in mitochondrial matrix this and all following steps only happen in mitochondria, with O_2 present $2\ NAD^+ + 2$ pyruvate + CoA → $2\ NADH + 2$ acetyl CoA + $2\ CO_2$
-CO_2	a waste product— diffuses out membranes and out of cell; opposite of photosynthesis, when 6 CO_2 are fixed into RuBP to make a glucose (in contrast, five more will be removed from the pyruvate)
-$2e^-$ -$2H^+$	comes off with CO_2, reduces NAD^+ electron carrier ($NAD^+ \rightarrow NADH + H^+$)
+coenzyme A (CoA)	enzyme similar to Rubisco which later catalyzes the carbon fixation in the Krebs cycle
acetyl CoA	final product of the pre-krebs, to be used in the Krebs cycle
2b. Krebs Cycle	takes place in mitochondrial matrix $6\ NAD^+ + 2$ FAD + 2 ADP + $2\ P_i$ + 2 coA → $6\ NADH + 2\ FADH_2 + 2$ ATP + $4\ CO_2$
+oxaloacetate (OAA)	OAA is the starting and finishing material for the Krebs cycle— it is always replenished and used; it is also found in C4 and CAM plants for carbon fixation
-CoA	CoA was used to help the carbon fixation of the acetate to the OAA, and breaks off for bonding again in the pre-Krebs cycle
citrate (citric acid)	six-carbon sugar; where the common name “citric acid cycle” comes from
-CO_2	a waste product— diffuses out membranes and out of cell; same two steps as in the pre-Krebs cycle, and will happen again with the alpha-ketoglutarate
-$2e^-$ -$2H^+$	reduces NAD^+ electron carrier ($NAD^+ \rightarrow NADH + H^+$)
alpha-ketoglutarate	five-carbon sugar

-CO_2	a waste product— diffuses out membranes and out of cell
-$2e^-$ -$2H^+$	reduces NAD^+ electron carrier ($NAD^+ \rightarrow NADH + H^+$)
—	energy from oxidative reaction powers ADP + $P_i \rightarrow$ ATP; substrate-level phosphorylation; can be used right away
succinate	four-carbon sugar
-$2e^-$ -$2H^+$	reduces FAD electron carrier ($FAD \rightarrow FADH_2$)
malate	four-carbon sugar
-$2e^-$ -$2H^+$	reduces NAD^+ electron carrier ($NAD^+ \rightarrow NADH + H^+$)
oxaloacetate	(go back to first step of Krebs cycle)
	Last step is separate— OAA is not the reactant. Also, now proteins are involved (not a metabolic pathway, but an electron transport chain, so steps will be written differently.
Oxidative Phosphorylation	happens in mitochondrial matrix 8-10 NADH + 2-4 $FADH_2$ (total of 12 high-energy electron pairs) + 26-28 (ADP + P_i) $\rightarrow$ 12 H_2O + 26-28 ATP (depending on amounts of NADH and $FADH_2$)
NADH -H^+ -$2e^-$	oxidation of the NADH to protein complex 1, the main energy source for powering ATP, hence the name "oxidative phosphorylation"; NAD^+ returns to the mitochondrial membrane or the matrix for more high-energy electrons from glycolysis or the Krebs cycle; the "electron transport chain" (ETC) begins here as electrons start to move in a series of "redox" reactions (each molecule is "reduced" and energized by the electrons, and then "oxidized" when it leaves)
pumping of two H^+	two protons are pumped by a pair of the high-energy electrons in the protein complex 1 from the intermembrane space to the matrix; rotenone (pesticide) poison bonds here and blocks the ETC
$FADH_2$ -H^+ -$2e^-$	oxidation of the $FADH_2$ to protein complex 2 (because protein complex one does not have the correct shape to accept $FADH_2$); these electrons do not pass through protein complex 1, and therefore provide less energy than the NADH (each pair passing through only 2 pumps, only pumping 4 H^+, and only creating 2 ATP instead of NADH with 3, 6, and 3, respectively)
carrying of electrons to protein complex 3	lower-energy electrons from protein complex 1 (NADH electrons) and 2 ($FADH_2$ electrons) are carried over by electron carriers to protein complex 3; usually a cytochrome acts as the electron carrier, because it helps catalyze redox reactions; also the reducing and oxidation are done by cytochromes in the protein complexes
pumping of two H^+	two protons are pumped by a pair of electrons; same as in protein complex 1
carrying of proteins to protein complex 4	same as carrying to complex 3

pumping of two H^+	final pump (third one for NADH electrons, second for $FADH_2$ electrons); same as in other complexes; cyanide and carbon monoxide blocks ETC here
$\frac{1}{2}O_2 + 2H^+ + 2e^-$	an oxygen atom and two hydrogen ions pick up the two depleted electrons from the end of the ETS to form H_2O; this is why oxygen is necessary for the Krebs cycle and oxidative phosphorylation to work: oxygen is the final electron acceptor, and without it the ETC would clog up and the mitochondria could not work; also helps keep concentration of protons inside the matrix low by using them up into water
H^+ passing through ATP synthase	protons travel from outside the matrix to inside through ATP synthase protein complexes: with three pumps and the depletion of H^+ by the creation of H_2O, the concentration of the protons outside the matrix are much higher than inside (unless with leaky membranes as with DNP or valinomycin— which can also be useful because it creates excessive heat and minimal ATP, such as during hibernation), and therefore they flow down their concentration gradient (chemiosmosis: facilitated diffusion of ions besides water); kinetic energy of two protons (one pair of electrons) passing through powers the phosphorylation of 1ADP + P_i to ATP; creates 32-34 ATP, which can be used immediately in the cell; DCCD and oligomycin are used to block ATP synthase