RESPIRATION

COMPETENCY: The learner appreciates how living organisms generate cellular energy, by analyzing respiratory processes and chemical breakdown of food within cells, to make informed decisions that promote good health and wellbeing.

LEARNING OUTCOMES: The learner should be able to;

a). examine the relationship between the structure of the mitochondrion and the stages of cellular respiration in living organisms. (u, s).

b). analyse the biochemical processes leading to ATP production in living organism, and how these processes are affected by physical activities and respiratory poisons (cyanide). (u,s, gs, v/a). (***details of biochemistry are not required.***)

LEARNING OUTCOME FOCUS.

- The ultrastructure of mitochondrion and the structural relationship of the mitochondrion to its function in ATP synthesis.
- The structure of Adenosine triphosphate (ATP) and its hydrolysis to release energy.
- The key stages of glycolysis and the molecules involved.
- The role of acetyl coenzyme A (Acetyl-CoA) in the metabolism of carbohydrates, lipids and proteins.
- The Krebs cycle (citric acid cycle) with focus on key steps (substrate level phosphorylation, decarboxylation and the production of NADH and $FADH_2$)
- The oxidative phosphorylation (the electron transport chain (ETC) with focus on the role of protein complexes, NADH, $FADH_2$ and oxygen.
- Effect of cyanide poison on the Electron Transport Chain.
- How ATP production changes during various exercise intensities.

Introduction

Large food molecules contain a lot of potential energy in the form of chemical bonds but it requires a lot of work to liberate the energy. Cells need a quick easy way to get energy for different purposes such as muscle contraction, synthesis of protein etc. and this is done with ATP. ATP is an unstable molecule, the bonds of which are easy to break making it a useful source of energy for cells. The energy released from this process is used to combine ADP with inorganic phosphate (Pi) to make ATP.

Definition

Respiration is a series of enzyme-controlled reactions that takes place in cells, in which energy within a nutrient molecule (e.g. glucose, lipid and proteins) is used to make ATP.

The site for respiration

The process of respiration takes place in the mitochondrion of a cell.

Mitochondria (sing. mitochondrion) are typically tubular or sausage-shaped or rod-shaped organelles about the size of bacteria. They are found in all types of eukaryotic cells.

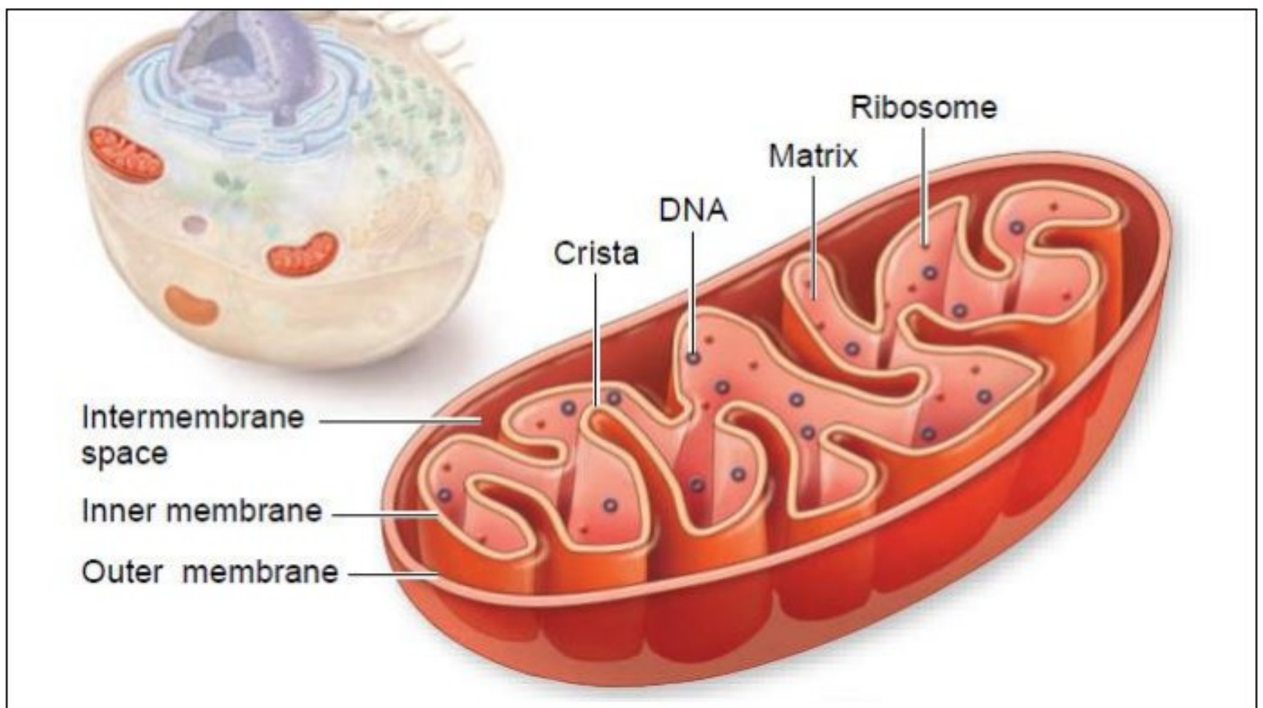
THE STRUCTURE OF THE MITOCHONDRION

Mitochondria are bounded by two membranes: **A smooth outer membrane**, and an **inner membrane** which is highly folded into structures called cristae (singular, *crista*).

The cristae divide the mitochondrion into two compartments:

-a **matrix**, lying inside the inner membrane;

-and an outer compartment, or **intermembrane space**, lying between the two mitochondrial membranes.



The structure of the mitochondrion

-The matrix contains enzymes and circular DNA, which directs or codes the synthesis of proteins within the mitochondria.

IMPORTANT TO NOTE

Mitochondria are prominent in organs where there's a lot of metabolic activity e.g. kidney nephron, muscle fibres, neuron axons, tail of the sperm and root hairs

The relationship between structure and function of mitochondria

- A mitochondrion is surrounded by an envelope (two membranes) that separate it from the cytoplasm, so that the reactions that take place inside it are not affected by reactions elsewhere in the cell.
- The inner membrane is folded to form cristae, providing a large area in which the carriers of the electron transport chain, and ATP synthase, can be embedded.
- The space between the two membranes (intermembrane space) is available to build up a high concentration of protons.
- The matrix of the mitochondrion contains all the enzymes needed for the Krebs cycle.
- The matrix of the mitochondrion also contains DNA and ribosomes, which are used to synthesize some of the proteins needed for the reactions of respiration.
- Narrow intermembrane space (gap between inner and outer membranes) enables pH / H+ / proton concentration gradient to be rapidly established / steeper chemiosmosis therefore more efficient / chemiosmosis can occur

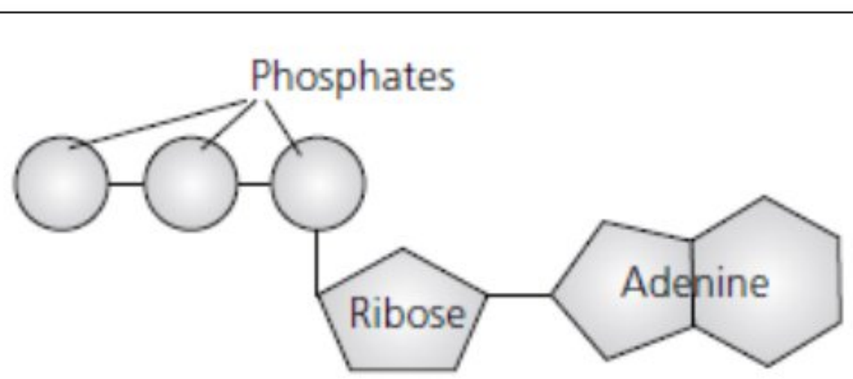
THE STRUCTURE OF ADENOSINE TRIPHOSPHATE (ATP) AND ITS HYDROLYSIS TO RELEASE ENERGY

ATP is a phosphorylated nucleotide and it has a similar structure to the nucleotides that make up RNA. It is an energy rich compound primarily synthesized during cellular respiration in aerobic and anaerobic cells. Oxidation of glucose, lipids (fats), and amino acids produce the ATP molecules inside cells

It consists of adenine, ribose, and a triphosphate all linked.

The adenosine is attached to the carbon atom of ribose which in turn is attached at the 5-carbon atom of sugar to a triphosphate group.

Three phosphate groups form a triphosphate. There are three phosphodiester bonds; one between phosphate groups, the second between the phosphate groups, and the third between the phosphate and ribose sugar. The first two are high energy phosphodiester linkage and produce energy during hydrolysis. Hence, hydrolysis of ATP to ADP (Adenosine Diphosphate) and again to AMP (Adenosine Monophosphate) yields energy, but the breaking of the phosphodiester bond between ribose and the phosphate requires energy



The structure of ATP

The energy released during the oxidation of these nutrients is trapped in the form of the high-energy phosphodiester bond in the ATP molecule.

HYDROLYSIS OF ATP TO RELEASE ENERGY

Hydrolysis is the process of breaking complex macromolecules apart. During hydrolysis, water is split, or lysed, and the resulting hydrogen atom (H+) and a hydroxyl group (OH–) are added to the larger molecule.

The hydrolysis of ATP using the enzyme ATPase produces ADP, together with an inorganic phosphate ion (Pi), and the release of free energy.

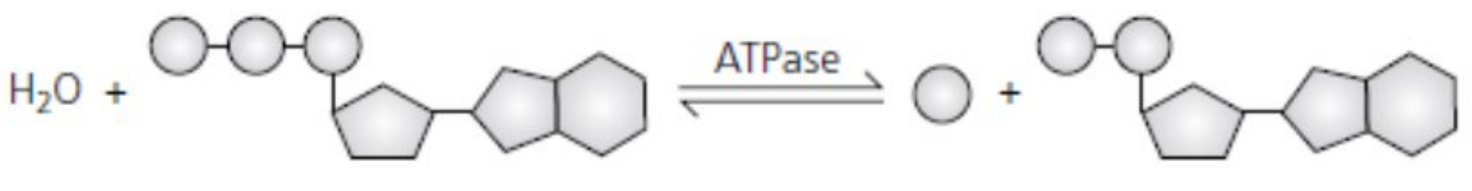
To carry out life processes, ATP is continuously broken down into ADP, and like a rechargeable battery, ADP is continuously regenerated into ATP by the reattachment of a third phosphate group.

Water, which was broken down into its hydrogen atom and hydroxyl group during ATP hydrolysis, is regenerated when a third phosphate is added to the ADP molecule, reforming ATP.

Energy must be invested into the system to regenerate ATP using the energy which comes from the metabolism of glucose.

In this way, ATP is a direct link between the limited set of exergonic pathways of glucose catabolism and the multitude of endergonic pathways that power living cells.

ATP is therefore used as the energy currency in every living cell.



ATP hydrolysis

Roles of ATP in living organism

Cells use energy for many different purposes. These include:

- synthesis of proteins and other large molecules from smaller ones, including DNA replication. These are examples of **anabolic reactions** — that is, energy-consuming reactions.

- Active transport of ions and molecules across cell membranes against their concentration gradient
- Transmission of nerve impulses
- Movement, for example muscle contraction (such as heartbeat, breathing movements, walking) or movement of cilia
- Production of heat to maintain body temperature at a steady level (in mammals and birds)

TYPES OF RESPIRATION

Respiration can take place in **aerobic** or **anaerobic conditions**.

In both cases, glucose or another respiratory substrate is oxidized.

In aerobic respiration, oxygen is involved, and the substrate is oxidized completely, releasing much of the energy that it contains.

In anaerobic conditions, respiration takes place without oxygen, and the substrate is only partially oxidized. Only a small proportion of the energy it contains is released.

Quick reminder

Oxidation-Reduction Reactions (Redox reactions)

Oxidation = the removal of electrons (or addition of oxygen)

Reduction = the addition of electrons.

These reactions are always coupled: one molecule must be oxidized while another is reduced.

COENZYMES

Respiration involves **coenzymes** called NAD, FAD and coenzyme A. A coenzyme is a molecule required for an enzyme to be able to catalyze a reaction.

NAD and FAD are reduced during respiration. The term 'reduce' means to add hydrogen, so reduced NAD has had hydrogen added to it.

Without the presence of NAD or FAD to accept the hydrogen, the dehydrogenase enzymes involved in respiration would not be able to remove hydrogen from their substrates.

AEROBIC RESPIRATION

Glucose (C6H12O6) and other respiratory substrates are split to release carbon dioxide as a waste product. The hydrogen from the glucose is combined with atmospheric oxygen. This releases a large amount of energy, which is used to drive the synthesis of ATP.

THE STAGES OF AEROBIC RESPIRATION

The chemical reactions of the aerobic respiration of glucose are grouped into 4 stages. The stages are; **Glycolysis**, the **pyruvate oxidation** also known as the link reaction, **the Krebs cycle** also known as the citric acid cycle and the **Electron Transport Chain (ETC).**

In eukaryotes the first stage (glycolysis) takes place in the cytoplasm (cytosol), and the remaining stages take place inside mitochondria.

Generation of ATP involves the addition of a phosphate to ADP and can be accomplished in two ways:

1. *Substrate Level Phosphorylation*: a high-energy phosphate is transferred directly from a substrate to ADP thus forming ATP.
2. *Oxidative Phosphorylation*: electrons are transferred from an organic compound to a cofactor carrier molecule (e.g. NAD+). The electrons are passed through other carriers (the electron transport chain) to a final acceptor (oxygen) and the passing of the electrons releases energy that is harvested to add a phosphate to ADP in a process called chemiosmosis.

1. GLYCOLYSIS

Glycolysis is the first stage of respiration. It takes place in the cytoplasm.

A glucose (or other hexose sugar) molecule is phosphorylated, as two ATPs donate phosphate to it. Phosphorylation helps to raise the energy level of the molecule, making it able to take part in the reaction.

This produces a **fructose 1,6-bisphosphate** molecule (6C), which splits into two **triose phosphate** molecules.

Another phosphate group from inorganic phosphate (P_i) readily available in the cytoplasm is added to each triose phosphate, forming two triose bisphosphate molecules.

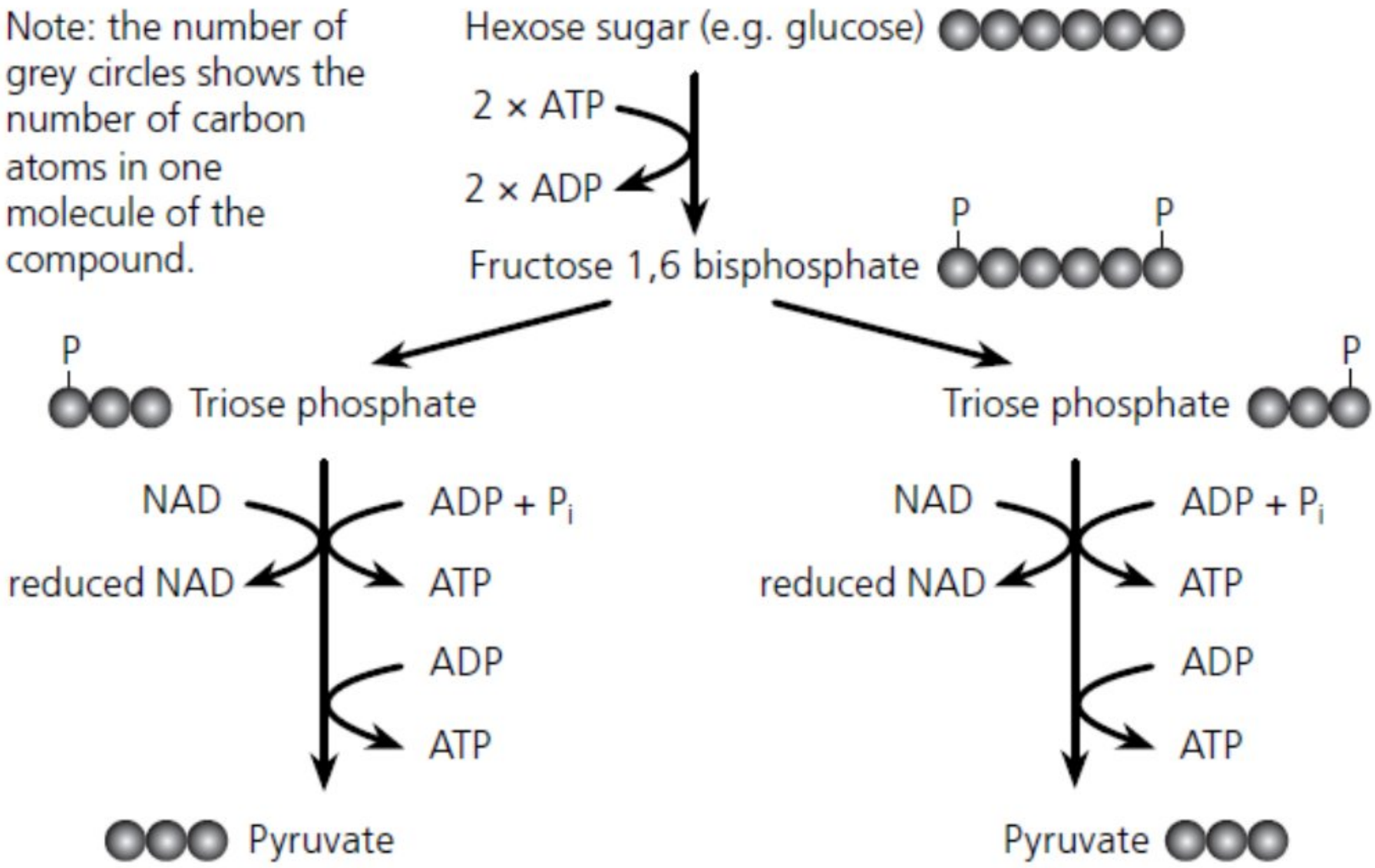
Each triose phosphate is oxidized to form a **pyruvate** molecule. This involves the removal of hydrogens by dehydrogenase enzymes.

The removed hydrogen ions are taken up by the **coenzyme NAD**. The removal of hydrogens is an **oxidation reaction**. It can also be referred to as **dehydrogenation**. This produces **reduced NAD (NADH)**.

During this step, the phosphate groups from the triose bisphosphates are added to ADP to produce a small yield of ATP, in substrate-linked reactions. This is an example of substrate level phosphorylation whereby, ATP is formed by the transfer of a phosphate group from a phosphorylated intermediate (in this case, the triose bisphosphate).

Overall, two molecules of ATP are used and four are made during glycolysis of one glucose molecule, making a net gain of two ATPs per glucose

Glycolysis occurs in the absence of oxygen but the next stage depends on the availability of oxygen.



Summary of glycolysis

2. THE LINK REACTION (PYRUVATE OXIDATION)

If oxygen is available, each pyruvate now moves into a mitochondrion where the **link reaction** and the **Krebs cycle** take place.

During these processes, the glucose is completely oxidized.

Carbon dioxide is removed from the pyruvate (**decarboxylation)**. which leaves the mitochondrion and diffuses out of the cell.

Hydrogen is also removed from the pyruvate, and is picked up by NAD, producing reduced NAD (NADH). This converts pyruvate into acetate molecule which is a 2-Carbon (2C) compound.

This immediately combines with coenzyme A to produce **acetyl coenzyme A (acetyl CoA),** which is also a 2C compound. The acetyl CoA then enters the next stage called the Krebs Cycle.

THE ROLE OF ACETYL CoA IN THE METABOLISM OF CARBOHYDRATE, LIPID AND PROTEIN

Carbohydrate metabolism

Complex carbohydrates such as starch are broken down into glucose which is then absorbed in the blood stream and transported to cells.

In the cytoplasm, **g**lucose is broken down to pyruvate via glycolysis and the pyruvate formed is converted to form acetyl CoA in the link reaction, entering the Krebs cycle for ATP production.

Lipid metabolism

Lipid metabolism begins with lipolysis, where triglycerides are hydrolyzed into glycerol and three fatty acids. Glycerol is converted to pyruvate in the cytoplasm and enters the mitochondria as acetyl CoA via the link reaction, while fatty acids undergo beta-oxidation in the mitochondrial matrix, producing acetyl CoA (each two-carbon fragment yields ~17 ATP, 1.5 times more than glucose per carbon). This process requires more oxygen and is slower than carbohydrate metabolism but provides higher energy output, making acetyl CoA a key link to the Krebs cycle for ATP production.

Protein metabolism

Proteins are broken down into amino acids during catabolism, typically in starvation when carbohydrates and lipids are scarce.

Amino acids undergo deamination (requiring vitamin B6), removing the amino group as toxic ammonia, which the liver converts to urea for kidney excretion. The remaining carbon chains of amino acids are processed.

ketogenic amino acids (e.g., leucine, lysine) are directly converted to acetyl CoA, while glucogenic amino acids (e.g., alanine, glycine) form pyruvate or Krebs cycle intermediates like oxaloacetate.

Acetyl CoA from ketogenic amino acids enters the Krebs cycle, combining with oxaloacetate to form citrate, which is oxidized to produce NADH, $FADH_2$, and GTP, fueling ATP synthesis via oxidative phosphorylation.

This process is less efficient for quick energy compared to carbohydrates or lipids due to the complexity of protein breakdown, toxic ammonia production, and the structural importance of proteins in cells.

3. THE KREBS CYCLE (CITRIC ACID CYCLE)

This stage takes place in the matrix of the mitochondrion.

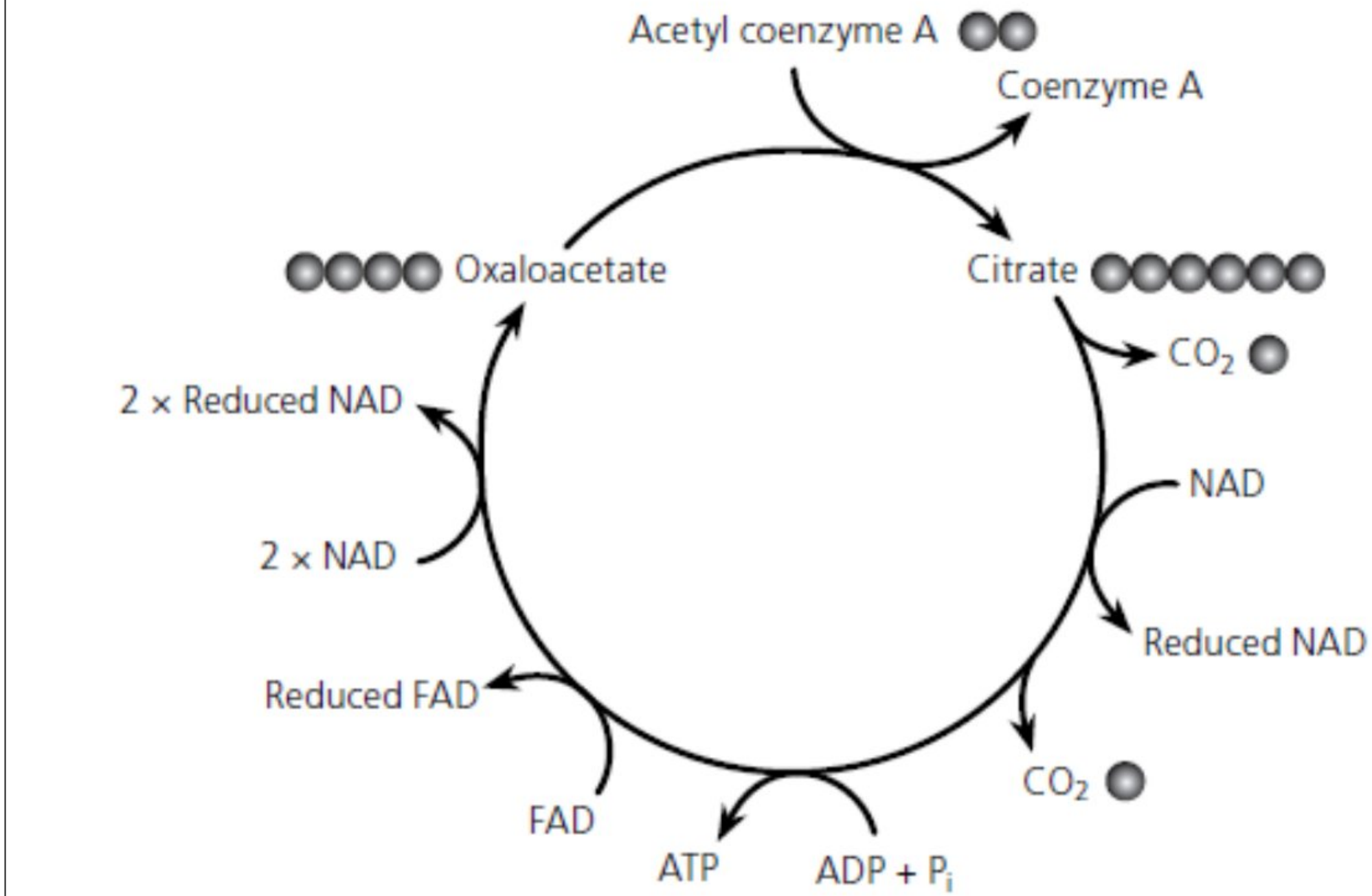
Each complete cycle results in the breakdown of an acetyl group. Acetyl groups are all that remain of the glucose that entered the glycolysis.

As the previous stages, Krebs cycle involves **decarboxylation, dehydrogenation and substrate level phosphorylation.**

Krebs cycle is a complex multistep and each is controlled by specific enzymes as summarized below.

- Acetyl CoA delivers an acetyl group to the Krebs Cycle. The two-carbon acetyl group combines with a four-carbon oxaloacetate to form a six-carbon citrate (citric acid), for this reason, the Krebs cycles is also referred to as the Citric Acid Cycle.

- The citrate molecule undergoes decarboxylation and dehydrogenation producing one reduced NAD and carbon dioxide, forming a five-carbon compound.
- The five-carbon compound undergoes further decarboxylation and dehydrogenation reactions which eventually regenerates oxaloacetate so that the cycle can continue.
- More carbon dioxide, two more reduced NADs and one reduced FAD are produced. ATP is also produced by substrate level phosphorylation.



The Krebs Cycle

FURTHER READING ON DETAILS OF GLYCOLYSIS

In reaction 1, the energy temporarily stored in acetyl CoA drives the formation of citrate from oxaloacetate. During this reaction, the CoA molecule is removed and can be reused by pyruvate dehydrogenase.

In reaction 2, the citrate molecule is rearranged to form isocitrate.

In reaction 3, a CO2 molecule, a proton, and two electrons are removed, converting isocitrate into α-ketoglutarate. This reaction releases a large amount of free energy, some of which is stored in NADH.

In reaction 4, α-ketoglutarate is oxidized to succinyl CoA. This reaction is similar to the oxidation of pyruvate to form acetyl CoA. Like that reaction, it is catalyzed by a multi-enzyme complex and produces CO2 and NADH.

In reaction 5, some of the energy in succinyl CoA is harvested to make GTP (guanosine triphosphate) from GDP and Pi. This is another example of substrate-level phosphorylation. GTP is

then used to make ATP from ADP and Pi.

In reaction 6, the succinate released from succinyl CoA in reaction 5 is oxidized to fumarate. In the process, free energy is released and two hydrogens are transferred to the electron carrier FAD, forming FADH2.

Reaction 7 is a molecular rearrangement in which water is added to fumarate, forming malate.

In ***reaction 8,*** one more NAD+ reduction occurs, producing oxaloacetate from malate, which is ready to combine with another acetyl group from acetyl CoA and go around the cycle again. The citric acid cycle operates twice for each glucose molecule that enters glycolysis (once for each pyruvate that enters the mitochondrion).

4. ELECTRON TRANSPORT CHAIN (OXIDATIVE PHOSPHORYLATION)

This is the truly aerobic part of the aerobic metabolism of glucose as this is where the oxygen is utilized. This is where most of the ATP produced from glucose is generated.

Oxidative phosphorylation is the final stage of aerobic respiration, occurring on the inner mitochondrial membrane. It involves the electron transport chain (ETC) and ATP synthesis via chemiosmosis, producing ATP, the cell's primary energy currency. This process utilizes electrons and protons derived from NADH and $FADH_2$, generated during glycolysis, the link reaction, and the Krebs cycle, with oxygen playing a critical role as the final electron acceptor.

The ETC consists of four protein complexes (I, II, III and IV) and mobile electron carriers (ubiquinone, or Q, and cytochrome c) embedded in the inner mitochondrial membrane.

NADH donates electrons to complex I (NADH-Q reductase), resulting in a significant drop in free energy as electrons are transferred to ubiquinone (Q). Concurrently, complex II (succinate dehydrogenase) transfers electrons from $FADH_2$, produced from the Krebs cycle, to Q.

Electrons from $FADH_2$ enter the chain later than those from NADH, leading to less ATP production due to fewer proton-pumping steps. Complex III (cytochrome c reductase) receives electrons from Q and passes them to cytochrome c, which then delivers them to complex IV (cytochrome c oxidase).

As electrons move through complexes I, III, and IV, the energy released drives the active transport of protons (H^+) from the mitochondrial matrix to the intermembrane space. This creates a proton concentration gradient across the impermeable inner membrane, with a higher H^+ concentration in the

intermembrane space than in the matrix. This electrochemical gradient represents stored potential energy required for ATP synthesis.

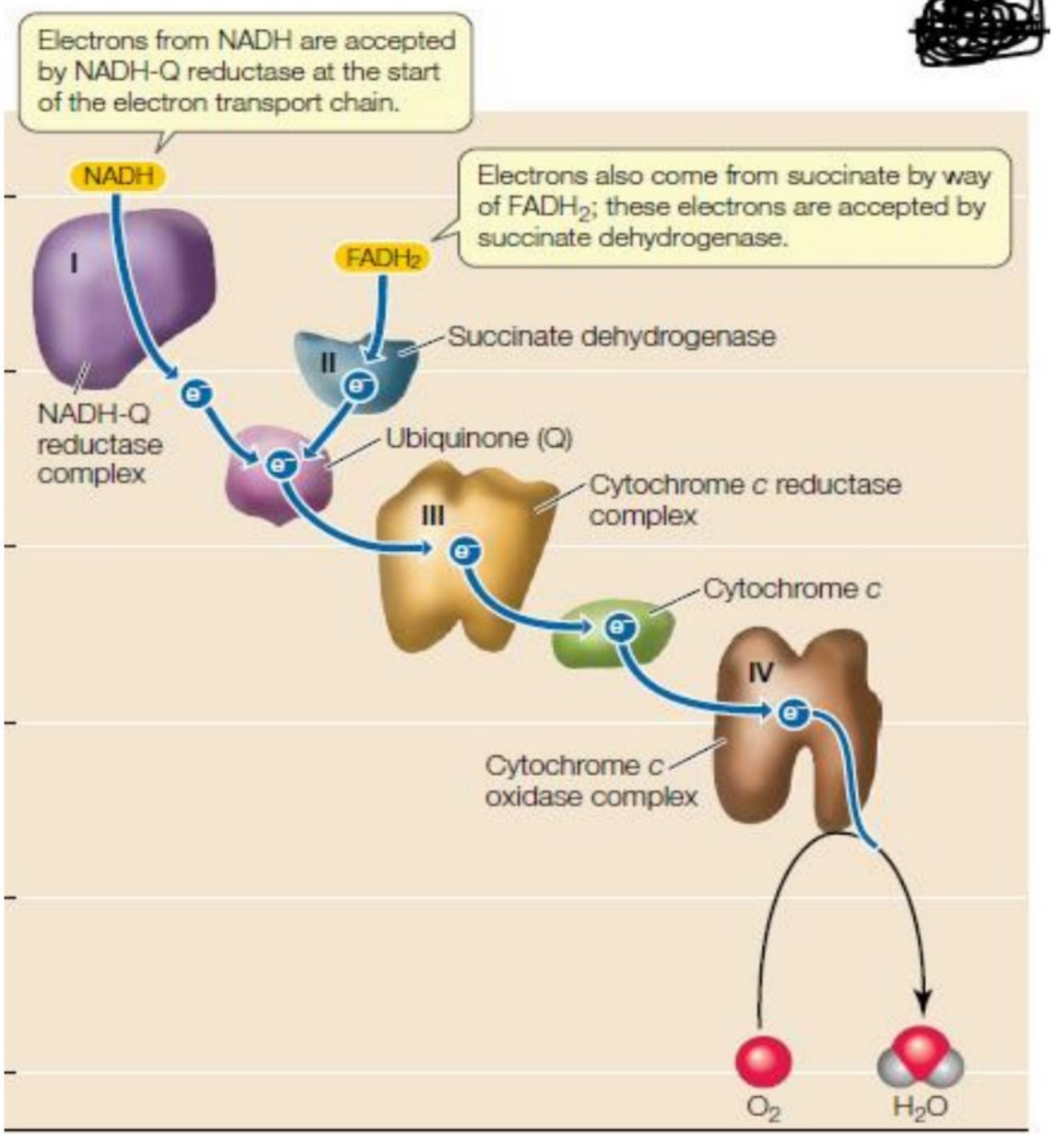
Protons return to the matrix via facilitated diffusion through ATP synthase, a specialized channel protein in the inner membrane. The movement of protons (chemiosmosis) causes ATP synthase to rotate, providing the energy to catalyze the combination of ADP and inorganic phosphate (Pi) into ATP. This process efficiently converts the energy from nutrient oxidation into a usable form for cellular functions.

At the end of the ETC, complex IV transfers electrons to molecular oxygen (O_2), the final electron acceptor. The electrons reunite with protons (H^+) from which they were originally split (from NADH and $FADH_2$), combining with oxygen to form water:

$$\frac{1}{2} O_2 + 2 H^+ + 2 e^- \rightarrow H_2O.$$

This reaction consumes two protons from the intermembrane space, further contributing to the proton gradient. Oxygen's role is essential, as it clears electrons from the ETC, preventing backup and enabling continuous oxidation of NADH and $FADH_2$. This ensures the ETC and ATP synthesis operate efficiently, linking nutrient breakdown to energy production in aerobic

The Electron Transport System



What happens when cells that are strict aerobes are deprived of oxygen?

Because oxygen is the final electron acceptor in the electron transport chain, organisms that respire aerobically require oxygen.

The last cytochrome in the chain retains its electrons when no oxygen is available to accept them. When that occurs, each acceptor molecule in the chain retains its electrons (each remains in its reduced state), and the entire chain is blocked all the way back to NADH. Because oxidative phosphorylation is coupled to electron transport, no additional ATP is produced by way of the electron transport chain.

Most cells of multicellular organisms cannot live long without oxygen because the small amount of ATP they produce by glycolysis alone is insufficient to sustain life processes.

Lack of oxygen is not the only factor that interferes with the electron transport chain. Some poisons, including cyanide, inhibit the normal activity of the cytochromes. (more detail will follow)

SUMMARY OF AEROBIC RESPIRATION

Stage (and site)	Summary of the process	Starting materials	End products
Glycolysis (in cytoplasm)	Series of reactions in which glucose is degraded to pyruvate; net profit of 2 ATPs; electrons are transferred to carriers; can proceed Anaerobically	Glucose, ATP, NAD^+, ADP, P*i*	Pyruvate, ATP, NADH
Formation of acetyl CoA (in mitochondria)	Pyruvate is degraded and combined with coenzyme A to form acetyl CoA; electrons are transferred to carriers; CO2 is released	Pyruvate, coenzyme A, NAD^+,	Acetyl CoA, CO_2, NADH
Citric acid cycle/ Krebs Cycle (in mitochondria)	Series of reactions in which the acetyl portion of acetyl CoA is degraded to CO2; electrons are transferred to carriers; ATP is synthesized	Acetyl CoA, H O 2, NAD1, FAD, ADP, P*i*	CO2, NADH, $FADH_2$ ATP
Electron transport and chemiosmosis (in mitochondria)	Chain of several electron transport molecules; electrons are passed along chain; released energy is used to form a proton gradient; ATP is synthesized as protons diffuse down the gradient; oxygen is the final electron acceptor	NADH, FADH2, O2, ADP, P*i*	ATP, H_2O NAD^+, FAD

EFFECT OF CYANIDE POISON ON THE ELECTRON TRANSPORT CHAIN

Cyanide is a highly toxic substance composed of carbon and nitrogen atoms, commonly found in compounds, such as hydrogen cyanide (HCN), potassium cyanide (KCN), and sodium cyanide (NaCN).

Cyanide is known for its rapid and potentially lethal effects on living organisms as it inhibits cellular respiration, thus halting the production of adenosine triphosphate (ATP), which is essential for cellular energy. This disruption prevents cells from using oxygen, resulting in rapid organ failure.

Cyanide is a highly toxic chemical compound that exists in various forms, including hydrogen cyanide, cyanide salts, and cyanogenic glycosides found in certain plants such as cassava, sorghum and apples.

Mechanism of cyanide poisoning

Cyanide poisoning exerts its lethal effects majorly by irreversibly inhibiting the cytochrome oxidase in the electron transport chain of the mitochondrion, thereby preventing cellular respiration.

The mechanism of this inhibition involves cyanide blocking the activity of an enzyme called cytochrome c oxidase (complex IV), a key enzyme in mitochondrial respiration.

This enzyme plays an important role in the production of energy in the form of ATP (Adenosine triphosphate) through oxidative phosphorylation.

The inhibition of cytochrome c oxidase prevents cells from utilizing oxygen, leading to cytotoxic hypoxia (a condition where cells are unable to use the oxygen delivered to them) despite adequate oxygen levels in the blood.

The resulting energy crisis forces cells to switch to anaerobic metabolism, which leads to lactic acid accumulation and metabolic acidosis.

The depletion of cellular energy subsequently causes widespread cellular damage, organ failure, and potentially death.

Signs and symptoms of cyanide poisoning

Cardiac Arrest. Cyanide's inhibition of ATP production disrupts cardiac muscle contraction and electrical signaling, causing arrhythmias. Energy-starved heart cells fail, leading to cardiac arrest and circulatory collapse.

Seizures. ATP depletion impairs neuronal signaling and membrane stability, causing hyperexcitability and uncontrolled electrical activity. Lactic acidosis from glycolysis worsens neuronal damage, triggering seizures.

Cyanosis. Cyanide prevents oxygen utilization by cells, leading to deoxygenated blood accumulation in tissues, causing bluish skin (cyanosis). This mimics hypoxia despite normal blood oxygen levels due to blocked cellular respiration.

Cherry-red skin coloration. Inability to use oxygen causes oxygenated hemoglobin buildup, giving skin a cherry-red hue, often seen in severe or late-stage poisoning. This reflects metabolic shutdown as cells cannot perform aerobic respiration.

sources of cyanide poisoning

Cyanides are present in a range of sources, such as mining, electroplating, the production of synthetic fibers, pesticides, and fumigation. Natural sources include plants that produce cyanogenic compounds known as
cyanogenic glycosides, such as cassava, apple and sorghum.

CHANGES IN ATP PRODUCTION DURING VARIOUS EXERCISE INTENSITIES

All the energy used by our bodies is obtained from the breakdown of food and drink. The three food nutrients that are used to generate this energy are protein, carbohydrate, and fat. Those are metabolized to create ATP, which is the source of fuel for all body processes, including muscle contraction.

Muscle contraction depends on the breakdown of ATP accompanied with release of energy which is used to power muscle contraction. Unfortunately, the cells (including muscle cells) can only store small quantities of readily available ATP, meaning cells have to constantly resynthesize ATP via other mechanisms, otherwise, muscle contraction would stop. This re-synthesis of ATP is done by the three energy systems.

1. ***The ATP-CP (ATP- Creatine Phosphate) or phosphagen system.*** This is an immediate system that uses preformed ATP and creatine phosphate.
2. ***The glycolytic system*** (anaerobic). This system metabolizes carbohydrates (glucose and glycogen) to lactic acid and pyruvate.
3. ***The oxidative system (aerobic).*** The oxidative system metabolizes carbohydrates or fats all the way to H2O and CO2.

These systems work together, but the intensity and the duration of the exercise determines which one is used the most.

ATP PRODUCTION DURING HIGH INTENSITY EXERCISE (e.g. Sprinting, weight lifting)

The first 10 to 20 seconds of high-intensity physical activity is fueled majorly by the ATP-CP, system. Once the available ATP is used up, which occurs in a few seconds, a molecule called phosphocreatine is broken down to regenerate ATP in the muscle. Creatine Phosphate therefore acts as a backup energy storage compound,

How the ATP-CP system works to produce energy during short and high intensity exercise

- The ATP that was initially stored the muscle is broken down into Adenosine Diphosphate (ADP) and single phosphate (Pi) to release energy for muscle contraction.
- Phosphor creatine is later broken down into creatine and a phosphate (Pi) by enzyme creatine kinase, releasing energy.
- The energy released from the breakdown of creatine phosphate is used to join ADP to free inorganic phosphate, forming ATP. This ATP can then be used to power muscle activity.

This energy system operates very quickly and can bring the highest output of the three systems. However, it is limited by the availability of Creatine phosphate in the muscle cells, which is usually consumed within 15 seconds of the high intensity exercise.

The body can eventually refill these stores when you rest.

This explains why;

- This system is the most active for athletes who engage in short and very intense, explosive movements as sprinting or powerlifting, jumping,
- A person can sprint at full speed for only a few seconds or lift maximum loads only 1-2 times before requiring rest or a decrease in exercise intensity using another metabolic pathway.

ATP PRODUCTION DURING MODERATE TO HIGH INTENSITY EXERCISE (e.g. Running 800, 200, 400-meter races)

The glycolytic pathway is the primary energy system used for moderate to high intensity exercise lasting from 15 seconds to 1 minute.

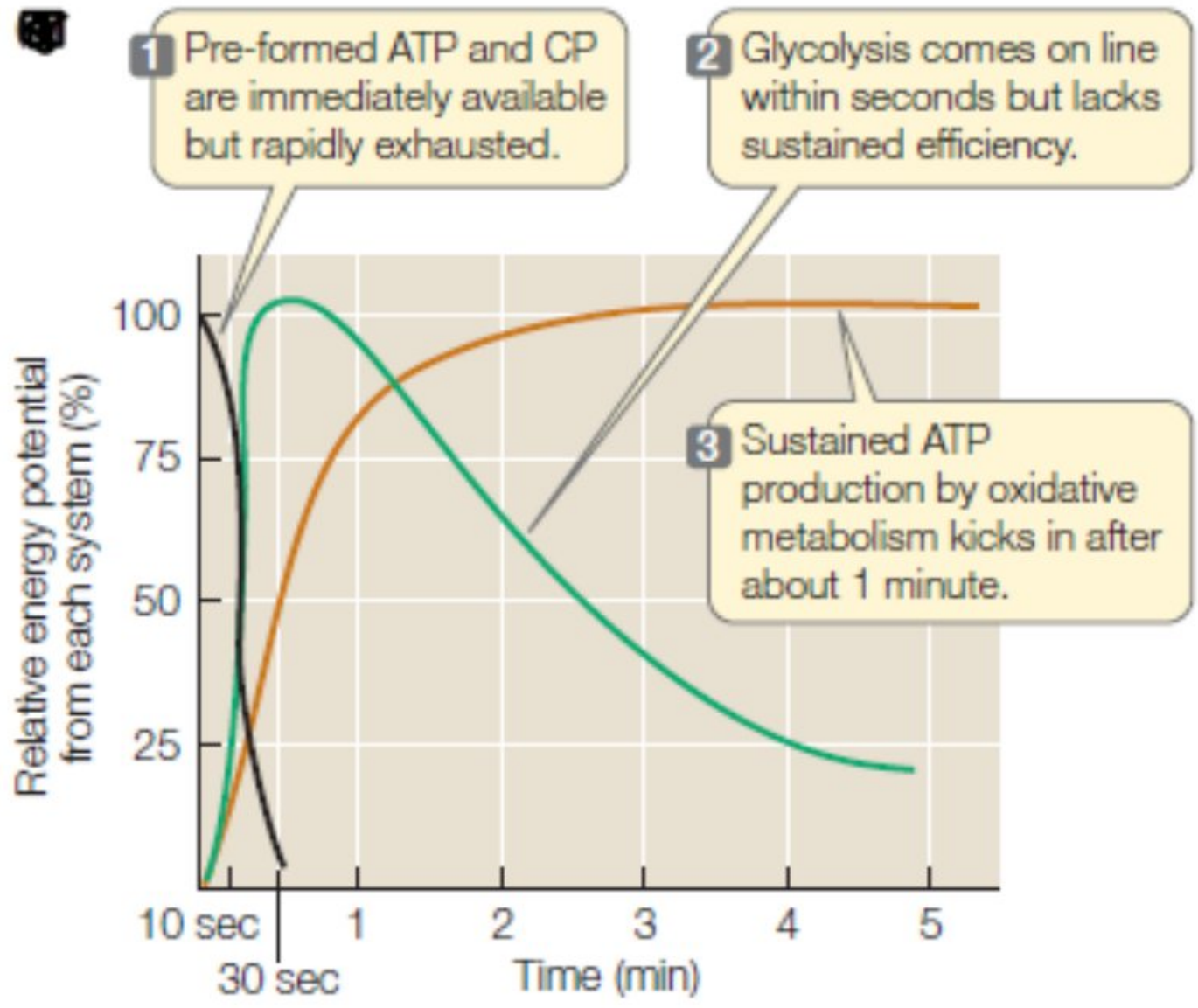
During a burst of strenuous exercise, the circulatory system cannot deliver enough oxygen to keep up with the demand of the rapidly metabolizing muscle fiber resulting into an **oxygen debt**. Under these conditions, this energy system breaks down the glucose stored in the muscle (glycogen) muscle fibers anaerobically (without oxygen) for short periods through glycolysis. This results into lactic acid

fermentation which is a method of generating ATP anaerobically, but not in great quantity. ATP depletion results in weaker contractions and muscle fatigue. Accumulation of the waste product **lactic acid** also contributes to muscle fatigue.

ATP PRODUCTION DURING HIGH INTENSITY EXERCISE (e.g. Running a marathon, jogging)

For exercise lasting longer than three minutes, the *oxidative* pathway is used. Unlike the others, this energy system requires oxygen. The increase in respiratory rate meets the oxygen demand during physical activity.

The oxidative system is slow, but is also the most efficient. Using fat as its primary energy substrate, it produces enough ATP to sustain longer duration activities, but only at submaximal exercise output. It means fat is the predominant fuel source used during low to moderate-intensity activity, like biking or jogging long distances.



The three energy systems during excersise

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