Sugar combustion and cellular respiration in the human body

Cells require energy to carry out metabolism. They receive this energy by "combusting" nutrients that we ingest with our food. The most important nutrients are carbohydrates, fats, and proteins. The different nutrients have different functions in the body. Carbohydrates, for example, act principally as energy providers to maintain the work of the muscles, the activity of all organs of the body, and body heat.
Carbohydrates can consist of monosaccharides, disaccharides, or polysaccharides. The two latter forms are broken down into monosaccharides (e.g., glucose) during the digestive process with the aid of various enzymes. The glucose diffuses from the intestine into the blood. The blood transports the glucose to the cells (e.g., muscle cells), where it is consumed and oxidized to water and carbon dioxide in the processes of cellular respiration (glycolysis, citric acid cycle, respiratory chain). These oxidation processes supply ATP (adenosine triphosphate) as a chemical energy store that can be used universally in metabolism.
The three subprocesses of cellular respiration take place in different areas of the cell. **Glycolysis** takes place in the cell cytoplasm, and the **citrate cycle** and **respiratory chain** take place in the mitochondrion. The most energy is produced in the respiratory chain. For this reason, the mitochondria are often referred to as the cell's "power plant". The higher the number of mitochondria in a cell, the higher the cell's energy requirement. Many of these "power plants" are found in cardiac muscle cells or in brain cells, for example.

The three processes of cellular respiration

Glycolysis

In glycolysis, the carbon skeleton of a glucose molecule with six carbon atoms is transformed into two molecules with three carbon atoms; the resulting compound is called pyruvate (or pyruvic acid).
Glucose is broken down in nine stages:

- In the first reaction stage, a phosphate group (P_i) is added to the glucose molecule. This process is called phosphorylation. It results in glucose-6-phosphate, which is higher in energy and can no longer pass through the cell wall.
- In the second and third stages, the molecule is converted into fructose-6-phosphate, which is split into two triose phosphates in two processes, using energy (ATP).
- Other conversion processes take place in the fourth through ninth stages, resulting in chemical energy in the form of ATP and NADH (nicotinamide adenine dinucleotide). NADH is needed later in the respiratory chain to synthesize ATP.
- The end product of glycolysis, pyruvate, is transported to the mitochondria for further energy production.

The gross equation of glycolysis is thus as follows:

$$\text{Glucose} + 2\ NAD^+ + 2\ P_i + 2\ ATP \rightarrow 2\ NADH + 2\ H^+ + 2\ ATP + 2\ \text{Pyruvate}$$

Citric acid cycle (citrate cycle)

Preparation for the citrate cycle

In preparation for the **citrate cycle**, the carbon skeleton of the pyruvate is reduced from three to two carbon atoms and bonded to the coenzyme A. In the process, carbon dioxide and hydrogen are released. The hydrogen is transferred to the coenzyme NAD^+, resulting in $NADH+H^+$. The resulting product is the reactive acetyl-coenzyme A (abbreviated acetyl-CoA).

Process of the citrate cycle

In the citrate cycle, the acetyl-CoA reacts with the oxaloacetate (oxaloacetic acid) already present in the cell to form citrate (thus the name citrate cycle), a molecule consisting of four carbon atoms. The citrate is broken down into oxaloacetate again in several reaction stages. The cycle starts again from the beginning. The purpose of these degradation processes is to produce hydrogen, which is transferred on the coenzyme NAD^+.

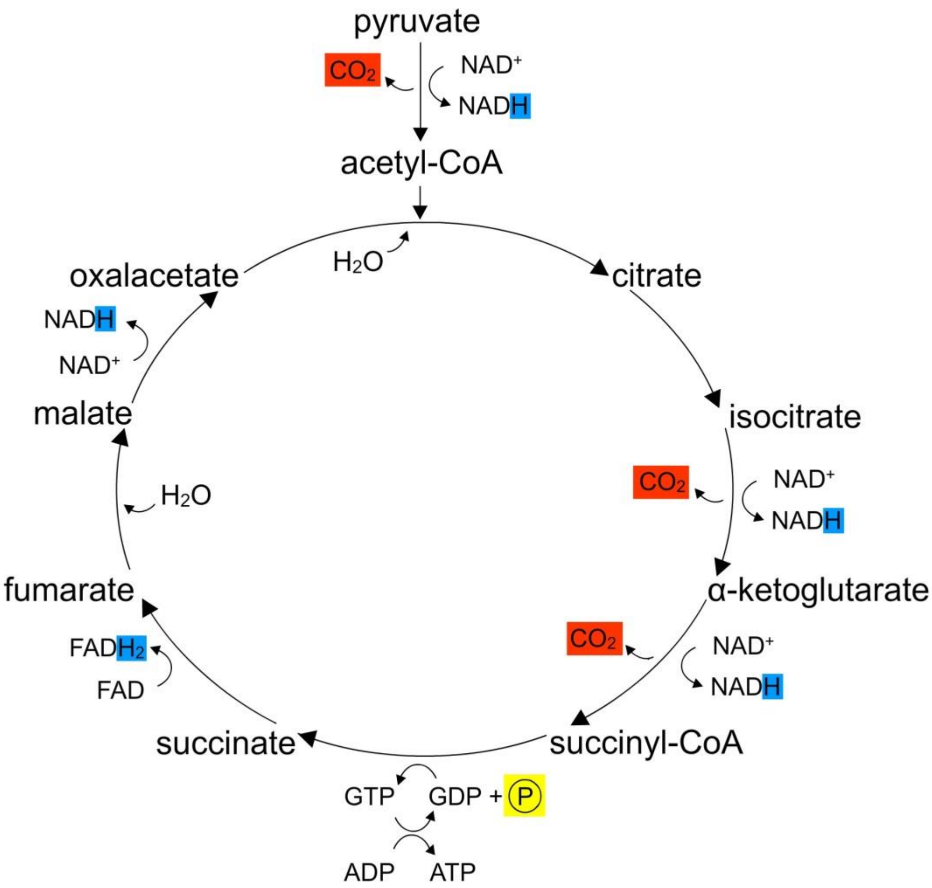

Fig. 1: The citrate cycle at a glance.

Citrate is broken down by means of several oxidation processes (see Fig. 1):

- In the first stage, citrate is converted into **isocitrate**. The isocitrate oxidizes into α-ketoglutarate by splitting off a carbon dioxide group.
- The **α-ketoglutarate** then oxidizes into succinyl-CoA, likewise by splitting off a carbon dioxide group. This process is also called oxidative decarboxylation.
- In the reaction of **succinyl-CoA** (succinic acid-CoA) to form succinate, the energy transporter GDP (guanosine diphosphate) is phosphorylated to form GTP, which then phosphorylates an ADP.
- The **succinate** (succinic acid) oxidizes to form fumarate. The hydrogen released in the process is transferred to the coenzyme FAD (similar to NAD^+).
- The **fumarate** reacts with water to produce malate.
- In the last stage of the citrate cycle, the **malate** (malic acid) is oxidized to form oxaloacetate again. The hydrogen acceptor is NAD^+.
- The **oxaloacetate** is now used again for a new cycle.

Respiratory chain and oxidative phosphorylation

The $NADH+H^+$ resulting from glycolysis and the citrate cycle is oxidized on the inner mitochondrial membrane with inhaled oxygen in the air (O_2). The reaction corresponds formally to the oxyhydrogen reaction and releases large amounts of energy:

$$2\,H_2 + O_2 \rightarrow 2H_2O + \text{energy}$$

This energy must not be released all at once, however, since otherwise an explosion would occur within the cell, which would destroy the cell. Therefore, the reaction takes place as a chain of successive biochemical redox reactions. In this process, electrons are transferred on the inner mitochondrial membrane between four protein complexes, so that only a tolerable portion of the total reaction energy is released at a time. This energy is used to pump protons (H^+ ions) from the mitochondrial matrix (fluid in the mitochondrion) to the intermembrane space of the mitochondrion. However, the protons will try to react with the electrons. This results in a proton flow in the intermembrane space along the inner mitochondrial membrane. The return of protons to the mitochondrial matrix is controlled by the enzyme ATP synthase, which uses the free energy to form ATP. This process is called **oxidative phosphorylation**. In the mitochondrial matrix, the returned protons and electrons now react with the oxygen in a controlled manner to form water.

Summary

The reaction products of human metabolism – carbon dioxide and water – occur in two different metabolic processes. While carbon dioxide is already generated in the citrate cycle, water is formed at the end of the respiratory chain. The reactions in the mitochondria also produce the reduced coenzyme $NADH+H^+$, which oxidizes to provide the energy for ATP synthesis.