Cytology: Definition and Basics

See online here

The concept of eukaryotic and prokaryotic cells is one of the foundational concepts of medicine. Each cell carries out specific functions depending on its structure and location. During the beginning of a new life, two cells are left on their own because cells function in large groups in an organism. Although the structure of the cells is similar in principle, important differences arise from the minutest changes, allowing cells to play different roles and enabling the whole organism to function.

Eukaryotes and Prokaryotes: Similarities and Differences
A cell is a tiny unit of an organism. Fundamentally, 2 types can be distinguished: prokaryotic and eukaryotic cells. Only bacteria, archaea, and cyanobacteria are among the so-called prokaryotes, and of these, bacteria are the most important for medical practitioners, since they often need to be controlled using antibiotics. There may be some similarities, but many differences can also be identified after studying the structure of these 2 cell types.

Both cell types are surrounded by a plasma membrane and their genetic information is contained in the cells. Similar metabolic pathways and principles of ATP formation can also be observed. Prokaryotic cells are significantly smaller, do not contain any cell organelles and, in contrast to eukaryotic cells, do not have a nucleus. Thus, their genetic material floats freely in the cytoplasm.

Eukaryotic cells contain a cytoskeleton and an inner membrane system in addition to the cell organelles. They have complex flagella, a spindle apparatus, and are capable
of endocytosis or, rather, phagocytosis, meiosis, and fertilization. Moreover, they have complex chromosomes and, in most cases, a diploid set of chromosomes.

\[ \text{Image: Cells of eukaryotes and prokaryotes, License: CC BY-SA 3.0} \]


In simple terms, eukaryotes consist of a **nucleus and cytoplasm** that contain various cell organelles that are surrounded by a **plasma membrane**. The appearance of the cells, both in terms of surface structure and their internal structure varies greatly depending on their respective functional tasks. The human body consists of about \(6 \times 10^{13}\) cells.

**The Nucleus**
An important component of almost every cell is the **cell nucleus** or **nucleus**. It contains DNA and thus provides the genetic information. Only **erythrocytes** do not contain **nuclei**. Other cells, for example, nerve or liver cells can be polynuclear. The shape of the cell nucleus is dependent on the cell. For example, even elongated nuclei can be observed in elongated muscle cells.

Constituents of the cell nucleus are:

- Chromatin
- Nucleolus
- Nuclear envelope
- Nucleoplasm

**Chromatin**

The DNA complex and some structural proteins in the cell nucleus, which can be dyed with basic dyes, are referred to as **chromatin**. Chromatin can be compressed into chromosomes in certain phases of the cell cycle. A distinction should be made between the so-called **euchromatin**, which is genetically active and is predominantly uncoiled, and the inactive **heterochromatin**.

Heterochromatin can be divided further into **constitutive heterochromatin**, which basically exists in condensed form, and **facultative heterochromatin**, which can exist in both condensed and non-condensed forms. Constitutive heterochromatin forms the **centromere region**. For example, a protein will never be seen in this material. Another example is the female sex gene, wherein one of the X-chromosomes is immobilized.

In mitosis, there are usually fully condensed **chromosomes**. For the organized flow of the non-condensed state, 2-m long DNA strands provide positively charged structural
proteins, which are referred to as histones. The histones H2A, H2B, H3, and H4 are wound by the DNA, whereas the H1 complex is positioned outside and the so-called linker DNA interconnects multiple nucleosomes.

Nucleolus

A structure from which ribosomes arise is referred to as the nucleole or nucleolus in the cell nucleus. It consists of a fibrillar center, the pars fibrosa, which contains DNA loops that encode ribosomal RNA, i.e. rRNA. Therefore, a high number of RNA polymerases can be found here. In the second part, pars granulosa, the synthesis of pre-ribosomal particles occurs: small and large subunits of the ribosomes and proteins are associated with each other.

In humans, the nucleolus forms around chromosomes 13, 14, 15, 21, and 22, and is referred to as the Nucleolus Organizer Region. Numerous rRNA genes are available here. Through the nuclear pores, ribosomal proteins are transported to the nucleus from the cytosol, and the rRNAs attach themselves and are processed. The large 60S and small 40S subunits once again leave the nucleus later and are assembled to form an 80S ribosome in the rough endoplasmic reticulum (rER).

Nuclear envelope

The nuclear envelope also referred to as karyolemma, is a double membrane and demarcates the nucleoplasm from the cytoplasm. A perinuclear gap which is 10–15 nm wide is located between the 2 membranes. The inner membrane, which faces the nucleus, has superposed lamin filaments, to which the chromatin strands are attached. The outer membrane facing the cytoplasm can be occupied by ribosomes and directly passes into the endoplasmic reticulum.

There are numerous pores (up to 1 million) for the exchange of substances on the surface of the nuclear envelope. Their diameter is about 10–26 nm. The transport of substances is actively done through the pores over ATP. Various proteins, such as importin, help in the selection of materials that are to be transported through the pores,
such as ribosomes, transcription factors or polymerase.

Nucleoplasm

The nucleoplasm is also called the karyoplasm or karyolymph. It contains about 10,000 times more sodium and chloride ions than the cytoplasm. Its mass balance serves the purpose of **DNA replication and transcription**, which occurs in the core area. All proteins that are required in the karyoplasm must be imported from the cytoplasm because **protein biosynthesis** takes place there.

The Cytoplasm

Each cell contains a cytoplasm. It consists of the cytosol, cytoskeleton, and various cell organelles in eukaryotic cells. About 80–85% of the cytoplasm consists of water, whereas 10–15% consists of proteins. Only a small mass thus consists of DNA, RNA, lipids, and other components.

Cytosol

Almost 55% of the cytoplasm is present in the cytosol. This is a gel-like mass that contains many proteins and enzymes. Hence, the cell is capable of synthesizing sugars, fatty acids, and nucleotides, for example, performing **glycolysis** and **protein biosynthesis** as well as the decomposition of the proteins again. The cytosol also serves as storage for glycogen and triglycerides.

Cytoskeleton

![Image: Cytoskeletal Components. By Phil Schatz, License: CC BY 4.0](image)

These are structured **protein filaments** inside the cells which handle the complex organization and processing that take place within the cell. The **actin filaments** and **microtubules**, as well as the intermediate filaments, are of particular importance. These are protein structures that, in addition to various other proteins in the cell, are responsible for tasks such as, **cilia activity** or **muscle contraction**, among other things.
Microtubules are **tubes made up of proteins** and enable the transportation of substances within the cell. They consist of **α- and β-tubulin dimers**. The α-tubulin is located in the negative pole and the β-tubulin is situated in the positive pole towards the **protofilaments** chain-like connected dimers. Nine triplets of microtubules form the wall of a **centriole**, a hollow tube in the cell, which is important for enabling the **polarity** of a cell during mitosis.

In doing so, the mitotic spindle, a network of approx. 3,000 microtubules, also play a role. The microtubules attach themselves to the chromosomes and pull them apart during anaphase, whereas, other microtubules separate the cell’s poles from each other. Consequently, the division in mitosis begins.

**Image:** Microtubule structure. By Thomas Splettstoesser, License: CC BY 4.0

**Actin filaments**

Actin filaments are **capable of interacting with other proteins** and are responsible for different tasks, especially movement. Actin filaments have 2 chains each with a positive and negative pole. Other than that, they are permanently linked to one another via interactions and are reciprocally twisted. Together with the molecule **myosin**, they are responsible for **muscle contraction**.

Myosin chains also have 2 chains, with a head at the end. These heads can bind to the actin filaments. The filaments steadily slide past each other causing the contraction of muscles, such that ATP-operated myosin heads always adhere elsewhere on the actin filaments. The principle of **ciliary movement** functions similarly: ATP-operated microtubules slide past each other and cause movement.

**The cell organelles**

**Ribosomes**
Ribosomes are RNAs that are linked to proteins. Ribosomes can be found in the rER, but are also freely present in the cytosol. Each ribosome consists of 2 subunits.

Their size can be determined through the respective rate of sedimentation in an ultracentrifuge. Note that the values of the large and small subunits cannot be added in order to determine the rate of sedimentation of the entire ribosome.

In this case, there is a significant difference between prokaryotic and eukaryotic cells: prokaryotic cells consist of 50S and 30S subunits, which together produce a ribosome with a sedimentation constant of 70S. For eukaryotes, 60S and 40S subunits result in 80S ribosomes. The aim of some antibiotic therapies is to intervene in the protein biosynthesis of prokaryotes.

Ribosomes are necessary for protein biosynthesis. When they are freely present in the cytoplasm and do not have a function, their subunits are separated. They are assembled only when a protein is to be synthesized. Free ribosomes produce proteins that are required by the cell. Ribosomes at the ER produce proteins, which are incorporated into the membrane wall or exit the cell.

**Endoplasmic reticulum**

ER can be differentiated into rER and smooth ER (sER). Both are a system of elementary membranes that consist of membrane tubules. Differences can be observed functionally, although both parts form a system together.

1. **Smooth endoplasmic reticulum**

   In contrast to rER, sER does not carry any ribosomes outside its membranes. It serves
as ion storage, handles hormone synthesis, allows carbohydrate metabolism, and also allows detoxification of medicines and other toxins. sER transmits the enzyme glucose 6-phosphatase, which is required for gluconeogenesis. Among other things, the metabolism of carbohydrates is regulated through this mechanism.

Because of the role it plays in the synthesis of hormones, plenty of sER can be found in the adrenal cortex for the production of corticosteroids and aldosterone. The sER is also required in the testes and ovaries, to produce sex hormones, testosterone, and estrogen. Similarly, the corpus luteum needs sER in order to produce progesterone.

Liver cells have a lot of sER whose purpose is to carry out detoxification. This applies, among other things, to barbiturates and alcohol as the excessive consumption of these substances allows sER to markedly multiply, enhancing the detoxification function. This mechanism can explain the development of tolerance to these substances.

The function of sER as ion storage is particularly important in muscle cells; sER, described here as the sarcoplasmic reticulum, stores extremely high amounts of Ca$^{2+}$ ions, which are released during an incoming nerve stimulus into the cytoplasm of the cell. Thus, the muscle cell is able to contract.

2. Rough endoplasmic reticulum

Ribosomes can be found in rER on the side that faces the cytosol of the cell. rER is thus a location of protein biosynthesis. As such, cells that must produce a lot of proteins, show a particularly high number of rER. Examples of such cells include pancreatic cells, whose purpose is to produce insulin, a proteo-hormone.

In order for a protein to be produced in rER and not in the free ribosomes, it carries a specific signal sequence. This distinction is important, as only proteins produced through rER are suitable for export from the cell. A signal recognition particle of the cytosol detects the signal sequence of the protein and binds the ribosome to the rER.

Golgi apparatus

Proteins move freely through the Golgi apparatus and are provided with post-translational modifications in this region. The Golgi apparatus appears like a stack of several
membranes, which are the so-called Golgi cisternae. Distinctions can be made between a convex cis-side, which faces the direction of the ER, and a concave trans-side, which faces the plasma membrane.

The proteins are placed over the transport vesicles on the cis-side of the Golgi apparatus and begin their way through the system from this point. When they reach the trans-side, they are either transported to the membrane surface or returned to the ER.

The Golgi apparatus therefore also has a sorting function in addition to the post-translational modifications.

**Lysosomes**

A lysosome serves as the cell for digestion. Lysosomes have an acidic pH so specific enzymes that are only active in an acidic environment can work within them. These hydrolytic enzymes are formed in rER and pass through the Golgi apparatus at its trans-side, where they are cut off in vesicles. Lysosomes originate in this way. During digestion by the enzymes, degradation products such as carbohydrates are produced, which are released into the cytosol of the cell.

**Peroxisomes**
Peroxisomes can be broken down resulting in a build-up of hydrogen peroxide, with the help of special enzymes. Moreover, they are capable of \(\beta\)-oxidation of long-chain fatty acids and steroid synthesis. They are often present in the myelin sheaths of axons in the brain, although pathological neurological changes during outages of peroxisomes are difficult to explain.

**Mitochondria**

Mitochondria are commonly referred to as the **powerhouses of the cell** since they produce ATP which is used for all energy-intensive processes. The biochemical process in which ATP is produced is based on a respiratory chain. The inner matrix space of the mitochondria is surrounded by 2 membranes: first by an **inner** membrane, then by an **outer** membrane.

The inner membrane bulges outward mostly in the form of cristae in the matrix space of the mitochondrion. A tubular type of surface enlargement is rare. The **inner membrane** is impermeable to most molecules, such that transporters are required in order to overcome this barrier. The **outer membrane** towards the cytosol is, on the other hand, permeable to ATP, NAD, and CoA through protein channels.

In addition to the respiratory chain, which is linked to the inner mitochondrial membrane, more enzyme-linked metabolic pathways occur in the matrix space. These include the citric acid cycle, which makes acetyl-CoA, oxaloacetate, and \(\alpha\)-ketoglutarate available for the oxidation process, and \(\beta\)-oxidation which provides, among other things, the hydrogen atoms for the respiratory chain.
References


**Legal Note:** Unless otherwise stated, all rights reserved by Lecturio GmbH. For further legal regulations see our [legal information page](#).