Biosignals from the point of view of biophysics/electrical biosignals in the organism

As it was said above, the physical nature of biosignals can be different: they can be mechanical, acoustic, thermal and other quantities. However, we most often associate the term biosignal with the electrical manifestations of the organism, which is why we dedicate this entire chapter to them. From a systemic point of view, when monitoring the electrical manifestations of the organism, it is possible to proceed in the hierarchy of the body structure from the lowest floors upwards:

Sub-cellular level

From the science of electricity, we know that the **uneven distribution** of electrically charged particles - **charges** - can be registered as **electric voltage** . As a result of the action of the **second law of thermodynamics**, we observe in non-living nature a movement aimed at equalizing such inequalities: the equalization of potential differences is caused by the movement of electric charges, which we can register as an **electric current** . A commonly cited example of such a phenomenon, accompanied **by entropy growth**, is the discharge of an electric cell through a light bulb. Both the filament of the bulb and the supply wires are metal; we know that free valence electrons are mobile carriers of electric charge in metals. In contrast, a galvanic cell works on an electrochemical principle: the conductor is an electrolyte and the passage of an electric current is realized by the movement of ions.

A similar situation also occurs in the organism, the essential part of which consists of **electrolytes** - aqueous solutions of acids, bases and salts, dissociated into anions and cations. In addition to the usual low-molecular substances, high-molecular substances, such as proteins, can also be charge carriers here.

If we want to monitor such processes, associated with the movement of charged particles in electrolytes, using their electrical activity, it is necessary to somehow bring the monitored signal to a suitable electronic measuring device, usually via a cable in which the signal is transmitted by electrons in metals. The question is, how does the electric current in the electrolyte, caused by the movement of cations and anions, be converted into the electric current caused by the movement of electrons in metals? Using electrodes. **Electrodes** are an important part of all examinations related to the investigation of electrical biosignals. The shape, material, size and construction of the electrodes vary greatly depending on the type of biosignal involved.

In contrast to inanimate and thermodynamically closed or isolated systems, we must think of living organisms as **open systems** that exchange energy, information and matter with their surroundings. As a result, they can remain in a **dynamically unbalanced state** for a long time , in which both processes that disrupt the balance and processes that restore it again operate - which is the essence of practically all life events in the organism. Most of these processes, as we already know, are accompanied by the **movement of electrically charged particles** , and thus we can record a number of **electrical phenomena** on every living organism . This allows us to use electrical biosignals to monitor and **diagnose** various events.

Cellular level

Membrane potential

We know that between two environments, separated by a semipermeable (semipermeable) membrane, we can observe **osmotic phenomena** , consisting of an uneven distribution of concentrations of various substances on both sides of the membrane. If the particles of dissolved substances carry an electric charge, this imbalance will manifest itself in the formation of different electric potentials on both sides of the membrane. This is a model situation that exists in virtually every cell. We refer to such a potential difference as the **resting membrane potential** .

The presence of a membrane potential plays a special role in excitable cells, such as **nerve and muscle cells** . In them, the difference in the concentration of **potassium ions**, which is 10-30 times higher inside the cell than in the extracellular space, contributes the most to its formation. The potential difference in such a case is described by the **Nernst equation**

$V_{K+} = (R.T / F). \ln ([K^+]_e / [K^+]_i)(40)$

indicating t**he equilibrium potential of potassium ions** V K+ as **proportional to the natural logarithm of the ratio of the concentrations of potassium cations in the extracellular [K +]**e **and in the intracellular [K +]**i **environment** . The constants are the universal gas R, the Faraday F, and T is the absolute temperature in Kelvin. After substituting normal values and body temperature into the equation, we get a potential of the **order of -50 to -100 mV** , which agrees quite well with the measured values. We would calculate more accurate values using **the Goldman equation** , which is similar to the Nernst equation, but also takes into account the **influence chloride and sodium ions** . **We measure the potential inside the cell relative to the extracellular space . The negative sign** therefore means that the internal environment is negatively charged compared to the surroundings.

Action potential

During the generation and propagation of a nerve impulse, the gradual opening and closing of various **ion channels** and thus the creation of an **electric current** , caused by the movement of ions. For a detailed description, we refer to the available literature. Here we limit ourselves only to stating that the gradual change in potential is manifested **by an electrical impulse with an amplitude** of the **order of 100mV and a duration of the order of 1ms** . The increase of the action potential is therefore a reliable indicator of depolarization of the cell membrane, while its decrease and gradual return to the resting state indicate its repolarization.

For direct intracellular measurement of the action potential of nerve or muscle cells, we would need to have a microelectrode at our disposal , which we could plunge into exactly one specific cell. Meeting such a requirement would be extremely challenging and practically unfeasible for clinical use. Therefore, direct intracellular measurement of action potentials is mostly limited to in vitro laboratory research.

Tissue Level

Summation Potential

The lowest level in the hierarchy, which can be used clinically, is the investigation of electrical manifestations of tissues. Although we are unable to isolate the signal produced by a single cell, we can sense the signal produced by a number of cells from a certain area where the sensing electrode is placed. The signal from the individual cells arrives at the sensing electrode through the extracellular space, which in this case can be imagined as a number of electrical resistors. This model connection allows us to understand the sensed biosignal as an approximate weighted arithmetical sum of signals from individual cells. The word "weighted" means, among other things, that the signal of more distant cells will usually be weaker (" near field potentials", as we mentioned in Sect. 2.2). Therefore, the word "sum" cannot be taken literally in such a way that, for example, a signal from a thousand cells, each producing 100mV, will add up to 10kV, which we will measure. In fact, the measured values of the summation biosignals are not an order of magnitude higher than the amplitudes of the action potentials that cause them.

Electromyography (EMG)

A typical representative of a biosignal, sensed from a certain area of tissue, is **an electromyogram** . This method can be **non-invasive** (EMG sensing with **surface** electrodes), but also **invasive** – sensing with **needle** concentric electrodes. When scanning with needle electrodes from a small area with the size of a fraction of a mm, we can also see the potentials of individual motor units. In contrast, the electromyogram, sensed by a surface electrode, is a typical summation potential, formed by a number of mutually overlapping signals from a large number of cells; its **frequency spectrum** it ranges from hundreds to thousands of Hz and is dependent on the activity of the examined part of the muscle. A signal with such a high frequency cannot be written directly on paper, so the doctor watches it on the screen, and it is also possible to **convert it into an acoustic signal** for assessment by hearing, when it is perceived as a crack or thunder.

Various computational methods are used for quantitative EMG evaluation. The level of muscle activity can be expressed, for example, as the sum of the absolute values of EMG changes per unit of time. We will calculate the EMG frequency spectrum using the fast Fourier transform.

Line Speed

As part of the EMG, the conduction velocity of the peripheral motor nerves is also often investigated. The examination consists in stimulating the nerve with an electric discharge (usually in the popliteal or elbow socket and on the ankle or wrist) and at the same time the reaction of distally located muscle groups is monitored electromyographically. From pathologically **prolonged latencies** , it is then possible to infer, for example, a **demyelinating disease** .

Organ Level

Using summation potentials, we can also investigate and map the activity of entire organs. The most well-known examinations are EEG and EKG.

Electroencephalogram (EEG) [edit | edit source]

EEG is a **standard non-invasive method** of functional examination of electrical activity of the CNS. Summation signals from neurons are sensed by electrodes **from the surface of the scalp** . The problem is that by passing through the relatively poorly conductive calf, the amplitude of the signal is attenuated to a level **of the order of tens of microvolts** . Given that the EEG signal is created as a result of the weighted summation of the activity of an **extremely high number of neurons** , we are no longer able to distinguish the individual action potentials of cells in the EEG signal, as, for example, in EMG. At first glance, the typical course of the EEG therefore has a rather irregular and chaotic course, in which we are sometimes able to see waves with a certain periodicity. The most famous is **alpha activity** with a frequency of about 12 Hz, which we observe in adults in the occipital region of the head when the eyes are closed. Slower frequencies (**theta** and **delta**) can be a pathological symptom in the awake state in adults. During sleep, on the other hand, they are an identifier of different sleep stages, which is used in sleep laboratories; in children, these frequencies may be a **measure of CNS maturity .**

The so-called 10/20 system (read **ten-twenty**) is used as a standard for the distribution of electrodes on the surface of the lbi, the name of which originated from the method of measurement, where the circumference of the head is divided into sections of 10% and 20%. In an analogous way, the measurement takes place in the remaining two perpendicular planes, the result of which is a network of points, reminiscent of the intersections of the meridians and parallels on the globe, according to which the electrodes are then placed in standard places. The electrodes placed most in front are called **prefrontal** , behind them there are a number of **frontal** electrodes , followed by **central** electrodes , then **parietal** electrodes and the most posterior are **occipital** electrodes . **We place temporal** electrodes on the sides.

EEG uses both basic **electrode connections** (see section 5.4), **unipolar** and **bipolar** . In the case of bipolar connection, we also differentiate according to the direction in which the chains are created, **longitudinal** (front-back direction) and **transversal** (left-right direction), or their combination.

Electrocardiography (ECG) [edit | edit source]

Given that ECG examination often serves as a model example of biosignal examination and as such is also part of biophysical practices, we will deal with it in a separate **chapter 6 .**

Evoked Potential

Evoked potentials usually mean the response of the CNS to stimulation of receptors by external stimuli. We have already discussed the mathematical model of evoked potentials in the theoretical part (section 2.4). It is essentially **a problem of identifying dynamical systems by introducing artificial stimuli** (most often a series of Dirac or other impulses) **at their input** . According to the physical nature of the stimuli, we most often distinguish EPs (evoked potentials):

- **VEP** (Visual EP)
- **AEP** (Acoustic EP)
- **SEP** (Somatosensory EP, somtosensory EP) – stimulation of peripheral nerves by electrical stimuli

We usually further divide these potentials according to their duration into **short , medium and long** . This latency is given by the place of their origin. The **first wave** , which we register with a delay of about 1ms, usually originates **directly in the sensory organ** (in the cochlea of the inner ear - cochlear EP, or on the retina of the eye - **ERG** = ElectroRetinoGram). We register several other short-latency waves in a time horizon of up to 10 ms. Thus, for example, during acoustic stimulation, these waves are generated in the nerve ganglia of the brain stem, that is why we call them stem potentials - **BAEP**(Brainstem Acoustic EP). As the nerve signals continue to progress, we record EPs with medium latency on the order of tens of ms, and finally we register EPs with long latency on the order of hundreds of ms, arising as a response of the cerebral cortex.

Neurologists, for example, mark evoked potentials in the above manner. If similar methods are used by an ear doctor to examine hearing, then they call it objective audiometry - **ERA** (Evoked Response Audiometry) or **BERA** (Brainstem ERA). We see that basically identical investigative methods can be called differently according to the purpose for which they are used.

The vector nature of the investigated signals

When investigating biosignals from whole organs or their parts, we are usually interested not only in their time course, but also in their **spatial distribution and spatial changes** , or the **projection** of this distribution on the surface of the organ or body. We provide such an examination by using a smaller or **larger number of electrodes** . The obtained signal then consists of several components, and these can be considered as components of a **time-varying vector** . Obviously, each such component requires its own entire transmission chain or channel. While some twenty years ago 3-channel ECG (later 6-channel) and four or eight-channel EEG devices were still used, nowadays the standard is 12-channel ECG and at least 16- or rather 21-channel EEG; 32-, 64- or even 120-channel devices are no exception.

In the case of ECG, for historical reasons, leads are spoken of instead of channels , which can sometimes lead to misunderstandings if one imagines one wire from an electrode under one lead, when one should imagine one pair of wires; although in the case of a 3-channel ECG, using 3 electrodes, such confusion is quite understandable. However, in this case of a triangle connection, each lead is represented by one side of the triangle, not a vertex. It is a particularly depraved trick of geometry that every triangle has not only three angles but also three sides, and each side has one pair of adjacent vertices.

Polygraphic record

The term "polygraphy", which we all use in connection with the bookbinding industry, has a completely different meaning in the medical clinic: it is a **simultaneous recording of biosignals of different (physical) nature .**

A typical representative is sleep polygraphy, used in **sleep laboratories** for sleep research and/or for the diagnosis of sleep disorders. As is known, during sleep it is possible to identify its various stages, characterized not only by changes in the EEG recording (e.g. the so-called stage of synchronous sleep, named after the synchronicity of EEG waves, generalized in different channels), but also by e.g. eye movement (REM phase of sleep - Rapid Eye Movements (characterized by rapid eye movements), limb movements and other motor activities (not to mention sleepwalking), changes in muscle tone, speed and depth of breathing, making various sounds, changes in heart

rate, blood flow to the skin and thus surface temperature, as well as changes in basal body temperature, sweating, changes in skin resistance, intestinal peristalsis, activation of the vegetative nervous system, blood supply to the genitals, etc., etc. If we want to register such changes as comprehensively and as thoroughly as possible, all that remains is for us to have at our disposal a dedicated special channel for each observed quantity, equipped at its input with a special converter (sensor). Leaving aside the sleep quality of the person under investigation, glued with a number of different sensors and tied to the apparatus with dozens of cables, the important thing is that we have demonstrated the essence of the polygraphic recording with a suitable example. The essence is that the investigated biosignal is made up of a time-varying vector whose components are physically incommensurable quantities (which can be simultaneously recorded on one wide strip of paper or just on a computer disk for further processing). plastered with a number of different sensors and tied to the apparatus with dozens of cables, the important thing is that we demonstrated the essence of polygraphic recording on a suitable example. The essence is that the investigated biosignal is made up of a time-varying vector whose components are physically incommensurable quantities (which can be recorded simultaneously on one wide strip of paper or just on a computer disk for further processing). plastered with a number of different sensors and tied to the apparatus with dozens of cables, the important thing is that we demonstrated the essence of polygraphic recording on a suitable example. The essence is that the investigated biosignal is made up of a time-varying vector whose components are physically incommensurable quantities (which can be recorded simultaneously on one wide strip of paper or just on a computer disk for further processing).

In a certain sense, the opposite of sleep laboratories are **stress laboratories** , which examine the organism in moments of its maximum strain. What they have in common with sleep laboratories is that even in this case we are dealing with polygraphic records, where, first of all, the ECG is registered continuously during the entire sports performance, and with it, as a rule, respiration together with a continuous analysis of exhaled gases (O_2 , CO_2 content) and other quantities monitoring the current state of the organism. Unlike sleep laboratories, they are not equipped with a bed for the examinee to sleep on, but with various (expensive) sports equipment that we would expect in exclusive gyms: tilting moving sidewalks, exercise bikes, etc. , speed of movement, power achieved. These examinations are intended both for top athletes, and for health monitoring in professions that require reliability during extreme performance (firefighters, professional army, special forces units), and occasionally also for patients whose health condition deteriorates in connection with physical stress. .

In contrast to physical performance, psychological performance is monitored in **psychophysiological** laboratories in correlation with its biological manifestations (EEG, glucose utilization in various parts of the brain, ECG, skin resistance, respiration, etc.) during the solving of various intellectual tasks, or various emotional loads. The instrumentation is again similar equipment for polygraphic recording, supplemented by various special panels and test equipment. Currently, instead of specially designed panels with different buttons, etc., various programs and situations simulated using a regular personal computer are advantageously used to solve individual tasks.

The basis of **sexological** polygraphy it again consists of polygraphic equipment, supplemented with special sensors that measure blood flow, temperature, volume changes, etc. in the areas of the genitals (phalloplethysmography). Projection of various erotically oriented scenes, images, sounds, texts, etc. serve as stimulation signals. Evaluation is carried out by quantitative evaluation of the correlation of measured biosignals depending on the nature of the stimuli presented. In addition to the diagnosis of functional sexual disorders, it is also used for forensic purposes and for the diagnosis of sexual deviations. The implementation of maximally objective methods is dictated here in particular by the requirement to draw up a strictly independent expert opinion, as a result of which the judiciary can decide on the order of treatment, the necessity of isolation, the degree of guilt, the possibility of correction and the appropriate punishment of the accused.

In addition to the differences that we have presented in the given examples, there are common principles for all such investigative apparatuses, which are the subject of the following chapter.

Examination apparatus

After a theoretical explanation and a few examples of clinical use, we will get a little more concrete about the situation we encounter when examining arbitrary signals or biosignals. One **part of the transmission system** is the **system under investigation** - in the given case, the patient's organism or some of its organs and parts (subsystems). The second (artificial) part of the entire system is the **examination apparatus**. In the previous chapters 3 and 4, we dealt with the generation and passage of the biosignal through the investigated organism. In this chapter, we will monitor the biosignal, which is sensed from the patient's body and transmitted to the apparatus, where it undergoes controlled processing. However, even though in the first case it was the passage of a signal through a living organism, and now the signal continues its journey through a constructed device, the same rules and regularities apply to it that we discussed in the first theoretical chapters 1 and 2.

Passage of the biosignal through the apparatus

It must be remembered that the patient, connected to the apparatus, in the presence of the examining staff and the entire environment of the examination room or laboratory, co-create a single system of interacting parts during the examination, and each of these parts participates in its own way in the outcome of the entire complex process. We can never reliably estimate to what extent and in what way the effect of all considered and unconsidered influences is reflected on the examination result, and it can only be our effort that the examination results depict the current state of the examined person or specimen as faithfully as possible. In order to succeed in practice, it is necessary not only to precisely and reliably master the clinical routine and gain the necessary personal experience, but in parallel with habitual stereotypes, it is necessary to maintain the most accurate idea of what is going on in the examination room. Biosignals have the characteristic that they are usually not very visible during their course and often appear only at the output of the entire chain, as a result of often complex transmissions, interactions and

transformations. It depends very much on the wit and good mutual communication of both the person who prepares and performs the entire examination, as well as the one who processes, interprets the examination results and based on them establishes a diagnosis - whether it is the same person, a well-coordinated team or the participants of this they don't even know the process and communicate only purposefully through paper or electronically transmitted messages. Not only every mistake, but also every non-optimality can take revenge, for example by mistaking an artifact for a biosignal or overlooking an important symptom hidden in the noise. as a result of often complex transfers, interactions and transformations. It depends very much on the wit and good mutual communication of both the person who prepares and performs the entire examination, as well as the one who processes, interprets the examination results and based on them establishes a diagnosis - whether it is the same person, a well-coordinated team or the participants of this they don't even know the process and communicate only purposefully through paper or electronically transmitted messages. Not only every mistake, but also every non-optimality can take revenge, for example by mistaking an artifact for a biosignal or overlooking an important symptom hidden in the noise. as a result of often complex transfers, interactions and transformations. It depends very much on the wit and good mutual communication of both the person who prepares and performs the entire examination, as well as the one who processes, interprets the examination results and based on them establishes a diagnosis - whether it is the same person, a well-coordinated team or the participants of this they don't even know the process and communicate only purposefully through paper or electronically transmitted messages. Not only every mistake, but also every non-optimality can take revenge, for example by mistaking an artifact for a biosignal or overlooking an important symptom hidden in the noise. interprets and based on them makes a diagnosis - whether it is the same person, a coordinated team, or the participants in this process do not even know each other and communicate only purposefully through paper or electronic messages. Not only every mistake, but also every non-optimality can take revenge, for example by mistaking an artifact for a biosignal or overlooking an important symptom hidden in the noise. interprets and based on them makes a diagnosis - whether it is the same person, a coordinated team, or the participants in this process do not even know each other and communicate only purposefully through paper or electronic messages. Not only every mistake, but also every non-optimality can take revenge, for example by mistaking an artifact for a biosignal or overlooking an important symptom hidden in the noise.

The **critical boundary** of the entire investigative system is precisely the **boundary between the person under investigation and the apparatus** . It can remind us of the membrane of a cell: the effort is to let the maximum of important information pass through and avoid as many disturbing influences as possible. At least half of the entire "science" of biosignals revolves around **artifacts**, which here (as opposed to artistic artifacts) are an extremely confusing and undesirable phenomenon. Experience and manual dexterity are just as important as intellectual proficiency: you can't think too long about Ohm's law and Kirchhoff's laws in the ambulance, you have to have them "in your blood".

During the transition from the patient to the apparatus ,**the biosignal often changes its character** . That's why we have to pay him due care right at his entrance, **during the acquisition** . The signal here is often weak, not yet amplified, particularly prone to breakdowns and various interference. Most of the **artifacts are created here, during the conversion or on the electrodes** . What we neglect during the acquisition, we hardly try to make up for it with more self-sophisticated a posteriori processing. At least a basic knowledge of all the physical phenomena that can interact with each other is essential. (The whole examination can be slightly invalidated, e.g. due to the high **transient resistance of the electrodes**, which must be remeasured and reduced in an appropriate way - by thoroughly cleaning and degreasing the skin, using contact gel, etc.)

Converters of physical quantities

In the introduction, we mentioned that biosignals, as well as signals in general, can have a different physical nature - electrical, mechanical, thermal, chemical, etc. However, for their further processing, it is expedient to convert them to a "common denominator", i.e. to one common physical size. At the present time, when electronic devices are at a very high technological and price-acceptable level, it has become a rule that signal processing takes place i**n electronic form** , where the relevant physical quantities are **electric voltage, electric current, electric resistance, frequency, etc**. Non-electrical quantities that we want to monitor, we usually have to convert at the beginning of the analog transmission chainin some way to electric. Devices that mediate such a conversion are generally called **transducers or sensor**s , or **converters , sensors , detectors** , etc. In some cases, it is more advantageous to carry out the conversion between different quantities **gradually** , e.g. we register the mechanical change optically and then convert the light signal into an electrical signal.

In the following overview, we will show some typical examples of the use of such converters.

Sensors of mechanical quantities

Position Sensors

- contact
- electrical switches, switches, etc.
- precision potentiometer: same principle as variable resistance (potentiometer)
- capacitive sensor: principle as for a variable capacitor (the mutual position of the plates changes) or the position of the dielectric (can also be used as a level gauge)
- electrolytic: the size of the wetted surface of the electrodes changes (typically: level gauge)
- induction sensor: principle: the relative position of the parts of the winding changes, or the coil core moves, the short winding, magnetic shielding, or the different windings that make up the transformer move relative to each other
- optical sensor: the light source, mirror, aperture, filter, reflective surface (as with an optical mouse) moves, etc.

- acoustic sensor: the transit time of an acoustic (usually ultrasonic) signal is measured
- dipole: an electric dipole rotates in the environment of the electrolyte (e.g. the eyeball)
- camera system: a video camera captures the scene, which is evaluated by computer
- dynamic imaging methods some imaging methods (X-ray, CT, sonography, etc.) make it possible to take a number of images in rapid succession and thus to observe the dynamics of spatial changes, similar to a film.

Rotation angle sensors

- similar in principle to position sensors
- the angle of rotation is converted to a change of position or vice versa using pulleys, rods, toothed racks, screws, etc.
- selsyn (inductive sensor – a design similar to two interconnected three-phase motors, where the rotation of one axis is electrically transmitted to the axis of the other selsyn)

Speed Sensors

- they can be in principle the same as position sensors, the speed is derived by differentiating the signal with time
- ultrasonic: the speed of approaching or moving objects changes the frequency of the received signal according to the Doppler principle
- radar: again they use the Doppler principle (similar to what the traffic police use)
- with the help of a pulley, it is converted into a rotary movement

RPM Sensors

- contact: the cam on the shaft switches the contact
- non-contact: capacitive, inductive, optical
- similar to position sensors
- alternator: works as an induction sensor, converting shaft revolutions into periods of induced voltage

Rotation speed sensors

- similar to sensors of the number of revolutions or the angle of rotation, the speed is derived by derivation
- tachometer: a rotating magnet excites eddy (Foucault) currents in the thread for a short time, and these cause a change in the moment of force, which is reflected by a change in the angle of rotation (like a tachometer in a car)
- tachodynamo: an unregulated dynamo whose magnitude of the induced voltage is proportional to the speed of rotation

Volume Sensors (pletysmographs)

- mechanical
- it is converted into a change of position by transfer
- capacitive
- the examined organ, located near one electrode, acts as the second electrode of the capacitor

Force sensors (force meters)

- spring: converts the magnitude of the force into a change in position according to Young's law of elasticity
- piezoelectric: produces an electrical charge on a piezoelectric crystal

Pressure sensors (pressure gauges, manometers)

- diaphragm deflection is converted to position or force measurements
- capacitive: the dielectric constant (permittivity) of the compressed gas changes

Mechanical strain gauges (strain gauges)

- resistive: the length and cross-section of the thin wire changes and thus its resistance
- optical: optical anisotropy of a transparent material, e.g. plexiglass, is created by mechanical stress

Fluid flow sensors (liquid and gas flow meters)

- with the help of various propellers and turbines, we convert it into rotary motion
- ultrasonic (they monitor the movement of microparticles in a dispersed environment, e.g. in blood)

Examples of the use of sensors of position, speed and other mechanical quantities

- detecting the position of the probe, e.g. in ultrasound diagnostics
- intraoperative navigation
- investigation of movement or mobility of the musculoskeletal system
- investigation of eye movements during sleep, reading, etc.
- investigation of the movement of internal organs, e.g. intestinal peristalsis
- examination of heart activity (echocardiography)
- monitoring the movement of the diaphragm
- movements during seizures

- stress tests
- sports medicine
- rehabilitation
- nystagmography (investigation of the balance system)
- dentistry (chewing)
- examined the heartbeat in various organs
- sexology (penile erection rate, vaginal contractions), respiratory function

Acoustic Sensors

Acoustic waves are mechanical waves, so we can use some of the principles of mechanical sensors mentioned above. The difference is in the higher frequency of the detected signals, either in the area of audible sound (approximately 16 Hz to 20 kHz) or in the area of ultrasound (from 20 kHz to tens of MHz)

We usually consider vibrations to be mechanical oscillations lying at the lower limit of audible sound, or below it (infrasound). In principle, we use similar sensors for sensing vibrations as for sensing sound or position, pressure, etc.

A **microphone** is a device commonly used to convert acoustic vibrations into electrical ones. The basic principle of the microphone is that air vibrations are transferred to mechanical vibrations of the diaphragm, which are further converted into electrical vibrations. We distinguish a microphone according to the physical principle used:

- carbon: compressing the grains of carbon powder changes the transition resistance between them; used in old phones, not very good quality
- crystal: principle of piezoelectric crystal
- capacitor: the membrane forms one electrode, a second, fixed one is placed near it; the dielectric is the air gap between them.
- dynamic: an oscillating coil is attached to the membrane, moving between the poles of a permanent magnet, in which a voltage proportional to the speed of movement is induced. For ultrasound sensing, we use transducers that work on the reverse principle than the transducers designed to generate ultrasound. In some cases, the same transducer can be used for generating and sensing ultrasonic waves. Piezoelectric transducers are most often used.

We usually process **ultrasonic frequencies using crystal grinding machines, which work on the piezoelectric principle.**

Temperature sensors

In its physical essence, temperature is also the mechanical oscillation of particles (molecules of a substance), but at such frequencies that the above-mentioned converters are useless for this purpose by themselves. **We use thermometers** or **temperature sensors** to measure the temperature . Temperature is a typical intensive physical quantity, which therefore cannot be measured directly; instead, we use the temperature dependence of different materials. "Classic" thermometers use the expansion of materials, which subsequently causes a mechanical change, and this can already be processed with the above-mentioned converters. This is mainly **a thermometer** :

- liquid: a change in the volume of a liquid, mostly mercury, manifested by a change in the height of the mercury column, which can already be sensed by contact (Vertex thermometers), optically, etc.
- gas: temperature changes cause pressure changes, registered by a pressure sensor
- vapour: structurally similar to gas, but it is not a volume expansion of the gas, but a change in the pressure of saturated vapors, i.e. an equilibrium state between two phases.

Thermometers working on these classical principles are, however, replaced in practice by much simpler and more reliable thermometers that convert t**he temperature directly into an electrical signal** :

- resistive: the resistivity of the material is temperature dependent
- thermistor: a thermistor is a semiconductor element with a significant thermal dependence

The above thermometers require that they be in close thermal contact with the measured environment. On the other hand:

- IR sensors take advantage of the fact that every body emits some thermal (infrared) radiation; its temperature can be determined non-contact by sensing this IR radiation using infrared phototransistors or photodiodes. The temperature distribution on the monitored surface can be monitored with an infrared camera (thermal imaging).

Use of temperature sensors

- measurement of body temperature in various places on the surface and in the depth of the organism
- ambient temperature measurement
- air or bath
- measurement of exhaled air temperature
- temperature measurement of applied solutions, served drinks and food
- virtually all biochemical reactions are accompanied by changes in temperature; by registering its progress over time, the dynamics of these reactions can be monitored
- it is also the simplest and least burdensome way to monitor respiratory function compared to, for example, a

plethysmograph or a flow meter, if we do not require measuring exact volumes of inhaled and exhaled air

Optical sensors

In modern times, we most often use semiconductor elements:

- phototransistors and photodiodes: change electrical resistance depending on illumination
- photocells: produces electrical voltage
- CCD elements: sensing elements of video cameras and digital cameras, allows to capture an image
- Vacuum components:
  - photon: the principle of the external photoelectric effect
  - photomultiplier: allows to register the weakest light intensities

Composite devices

- colorimeter: it can, for example, contain several sensors sensitive to different wavelengths of light; therefore, it can detect the different representation of its components, hence the color and its changes
- spectrophotometer: light is split into a spectrum using a prism or a diffraction grating and its intensity is measured as a function of wavelength

Photographic Techniques

Images taken using traditional photographic methods can then be processed using a photometer or digitized using a scanner.

Use:

- a large part of other physical quantities is advantageously first converted to the measurement of optical quantities (see above)
- possibility of non-contact sensing, lower failure rate than mechanical contacts and other moving parts. We use visible or infrared radiation.
- measurement of luminescence of some organic substances

Extinction measurements

Extinction means absorption of light. In order to measure extinction, in addition to the light detector, we also need its source. As light sources we use:

- light bulbs
- discharge lamps
- LEDs (Light Emitting Diode)
- laser diodes
- lasers

Sometimes we are also interested in the dependence of the extinction coefficient on the wavelength of the transmitted light. in that case, we either gradually change the wavelength of the monochromatic light source (with a monochromator, filters, different colored LEDs, etc.) or we irradiate the sample with a composite spectrum (eg white) and use a colorimeter for detection.

Use:

- plethysmography: the change in tissue volume can be registered as a change in the intensity of the transmitted light
- e.g. for monitoring the pulse on the finger while monitoring vital functions
- a large part of biochemical reactions is accompanied by changes in extinction (color changes) or other optical properties. By measuring absorption in the infrared region, we can measure e.g. CO 2 concentration in blood and tissues (**capnometer**).

Ionizing radiation detectors

The detection of ionizing radiation is discussed in detail in scripts [5]. We mention it at this point in the context that temporal changes in the intensity of ionizing radiation arising in an organism or passing through an organism can also be understood as a biosignal. Of the detectors, we are mainly interested in those whose output is in the form of an electrical signal, e.g. a photomultiplier or a scintillation detector in conjunction with a photomultiplier etc. The radiation captured on the photographic material can then be processed photometrically or with the use of a scanner.

Electrodes

If the biosignal is essentially electrical, it is usually not necessary to use any of the above-mentioned converters. Electrodes remain the basic method of sensing biosignals from the patient. Although the use of an electrode may seem relatively straightforward and easy compared to various complex transducers of non-electric quantities, the opposite is true. The demands on the quality of the used electrodes are often extreme, and although the purchase price of the electrodes may seem negligible compared to expensive equipment, it is not worth saving too much here.

The electrode is a part of the apparatus, **mediating the passage of electric current** between the patient and the apparatus . As such, it comes into direct contact with the patient's body and therefore its material and construction are subject to strict requirements.

Electrodes can be divided according to various criteria. We will list here only the most basic methods of division and the most common variants.

Purpose

- diagnostic
- therapeutic

(In this section on biosignals, we will focus mainly on electrodes for diagnostic devices.)

According to the function and direction of signal passage

- sensing (lead the signal from the patient to the apparatus)
- stimulating (lead the signal from the apparatus to the patient's body)
- auxiliary (shielding, grounding, protective, etc. ensure or improve other examination conditions)

Material

- metal (silver, platinum, gold, stainless steel, various alloys, etc.)
- non-metallic (glass capillaries, filled with electrolyte)

Face

- flat (disc, cylindrical, strip, etc.)
- needles

Shape and location

- superficial (usually superficial, they are in contact with the surface of the skin)
- needles (penetrate under the skin to muscles and other organs)
- special (introduced in certain places – on the cornea, in the vagina, in the rectum, in the esophagus, on the surface of the dura (meninges), subdural electrodes, etc.)

(according to the location of the electrodes mentioned above, we also divide the examination into invasive and non-invasive)

According to the number of electrically isolated parts - especially for needle electrodes

- monopolar (they are connected with a single-core cable, they work as active or reference)
- concentric – the active electrode is placed inside a hollow needle, the outer surface of which serves as a reference electrode.
- bipolar (two wires right next to each other, one works as active and the other as reference, the potential difference between them is sensed)
- multiple, multi-lead (contain a large number of sensing surfaces)

According to the number of uses

- one-use only
- for repeated use

According to the method of attachment

- held (e.g. by rubber straps)
- self-adhesive
- absorbent

According to the time of application

- short-term (for one examination)
- long-term (e.g. all-day and multi-day)

Differential Amplifier

The electrical potentials sensed by the electrodes have a very **low amplitude** : for example, in the EKG it is a voltage of the order of millivolts , in the case of an EEG the voltage is about 100 times lower, **in the order of tens of microvolts** ; for evoked potentials, the useful signal is measured in microvolts . Such low voltages must first be amplified so that they can be further processed.

A problem closely related to the low amplitude of monitored signals is the **noise problem** . In today's industrialized society, we live in an environment filled with "electromagnetic junk" of all kinds; they are transmitted not only by television and radio transmitters and mobile phones, but also by computers and virtually any electrical

line. In the hospital environment, the use of a whole range of other electrical devices adds to this ballast - electrotherapy, operating rooms, anesthesiology-resuscitation departments, X-rays and other imaging techniques, etc., etc. are constant sources of electromagnetic interference.

In the past, it used to be the rule that e.g. EEG devices were placed in **Faraday cages** : originally it was a cage made of wire mesh or wire mesh with carefully electrically connected connections and a ground that serves as a shielding cover. The Faraday cage can also be solved by placing a grounded wire mesh on or under the plaster. Currently, the use of such building modifications is limited due to financial costs. Therefore, it is necessary to minimize induced interference voltages, both by the design of the device and by careful positioning of the electrodes on the patient's body.

An **input amplifier** is used to amplify small signals . **One way to minimize the effect of interference is to use an input amplifier in a differential circuit, a differential amplifier for short, to amplify low signals** . It is a sensitive amplifier with high voltage gain and two inputs, one direct (active) and the other inverted (reference). A differential amplifier works by amplifying the voltage **difference** (difference) between the two inputs: i**t subtracts the voltage at the reference input from the voltage at the direct input and then amplifies only the resulting difference**. One point of this connection is that if a signal from the electrodes is applied to both inputs, and an equally large interfering voltage is induced at both inputs, then this interfering voltage will subtract from each other and will not show up at the output of the amplifier.

Connection of electrodes, leads

The second consequence of using differential amplifiers is the fact that we can connect two electrodes to one amplifier with two inputs. For example, in an invasive EMG examination, we use a concentric needle electrode consisting of two conductive parts: an insulated wire is placed in a hollow needle, similar to an injection needle; the bare end of this wire acts as a single electrode (active) that connects to the direct input of the differential amplifier, while the outer surface of the needle acts as a reference electrode that connects to the inverting input. As a result, we get an amplified signal at the output of the amplifier, proportional to the instantaneous potential difference between the tiny surface of the active part of the electrode and its surroundings, formed by the hollow needle. In this way, we can detect signals from a very limited area (a fraction of a cubic mm) of the tip of the needle electrode. The signal from such an electrode is guided along the device by a shielded cable, where the core of the cable leads the signal from the active electrode and the shielding sheath leads the signal from the reference electrode; in this way, even during the transmission of the signal from the electrode to the amplifier, interfering voltages cannot be mixed with the signal.

In the case of using surface electrodes (e.g. with non-invasive EMG), we must use at least two such electrodes: one active one, which we connect to the direct input, and a reference one, which we connect to the inverted input. (When using simple cables, there is a risk that unwanted disturbing voltages will be induced in the loop that is created in the space between them, so it is good to lead these leads as close as possible to each other.) In this way, we amplify the voltage difference in the place between the two electrodes: this is how we typically obtain a summation potential from a large number of nerve or muscle cells.

Bipolar Wiring

An interesting situation arises if we want to simultaneously register a signal from a larger number of electrodes. Then we need our equipment to be equipped with a greater number of differential amplifiers. One option is to connect electrodes in pairs to the inputs of differential amplifiers; such connection of electrodes is called **bipolar** and is characterized precisely by the fact that it amplifies the difference between two "equal" electrodes. With this solution, however, we would need two electrodes for each amplifier, i.e. double the number of electrodes compared to the amplifiers.

Therefore, here is the solution used by Einthoven in his EKG device: he imagined the three electrodes, placed on the three limbs, as the vertices of an imaginary triangle, the sides of which created the vectors of differential voltages, which he led to the galvanometer (at a time when there were no amplifiers, so the two terminals of the galvanometer showed the voltage difference between them). Thus, from the three electrodes (R=right hand, L=left hand, F=left foot), he obtained three possibilities for connecting the galvanometer, which in the case of ECG are called leads - they are combinations of LR, FR, FL (called I., II., and III Einthoven's lead). Even though Einthoven connected the galvanometer in this way step by step (it was an expensive device, at first it only had one), in principle it is possible to connect galvanometers (or differential amplifiers) to three electrodes three at a time in this way, and it is still a **bipolar wiring** .

Such a bipolar connection can also be used in other examinations, e.g. EEG, where we use several tens of electrodes distributed over the surface of the scalp. The common principle of this connection is that one electrode is connected simultaneously to two inputs of different (adjacent) amplifiers; in this way not only closed cycles (as in the case of Einthoven's triangle) but also open chains can be formed. However, it always applies that the potential difference between two adjacent electrodes is amplified.

Unipolar Wiring

Sometimes, however, it is not enough for us to observe only the difference **between** two adjacent electrodes, but we would be interested in the course of the signal **under** which electrode. If we connect this electrode to the direct input, where do we connect the remaining reference input? The answer is perhaps fundamentally twofold: **Either** we use one electrode, which we place somewhere outside the other active electrodes, and this will be the common reference electrode for the interconnected reference outputs of all differential amplifiers. Orwe artificially create

some electrically "neutral" point, for example by connecting all active electrodes via resistors of the same size to one point, where (on the same principle of superposition as is created for e.g. the summation potential) an arithmetic average of the potentials of all electrodes. (Equally large resistor sizes provide equal weights for this weighted **average** —as we explained in Section 2.2.) In the case of the EKG, such an electrical center of an isosceles triangle is called a Wilson clamp . Then the signals from the individual active electrodes create vectors that all emanate from this one common center to the vertices of the triangle (Goldberg leads).

This principle is also used in other examinations, e.g. EEG, where the individual leads are not called Goldberg leads, but we simply talk about unipolar **connection** .

Channels

The output of an appropriately connected amplifier (whether it is a bipolar or unipolar connection or a signal from a sensor, sensor, etc.) is called **a channel** . The channel only passes one biosignal, be it a single ECG lead or something else. In principle, this means that we need one input amplifier for each channel. How many channels the equipment is equipped with, how many different signals it can pick up and process. During the progress of the signals through individual channels, it is possible to modify the signals in electrical form in various ways. A typical matter is the use of adjustable filters.

Filter

Frequency filters are an example of linear dynamic transmission systems , as we talked about them in section 2.4, and therefore at this point we will use the knowledge of transmission characteristics discussed in section 2.5.

E.g. we require the bandpass filter to transmit frequencies in a given bandwidth (in the frequency band defined by the cutoff frequencies f 1 , f 2) as far as possible without weakening the signal (equal amplitude characteristic in this bandwidth) and, on the other hand, to filter out all other frequencies:

A(f) = 1 for f 1 <= f <= f 2 (41a)

A(f) = 0 for f < f 1 or f 2 < f (41b)

Otherwise, we call a filter that passes all other frequencies except some in the specified range a notch filter :

A(f) = 0 for f 1 <= f <= f 2 (42a)

A(f) = 1 for f < f 1 or f 2 < f(42b)

The amplitude characteristics of such filters would ideally be rectangular, having the shape of rectangles with steep edges, lying at the lower and upper cut-off frequencies of the filter. Similarly, it would be low-pass and high-pass:

A **low-pass filter** is such a filter that passes only those frequencies that are lower than the cut-off frequency of the filter f 0 , while retaining all signals with a higher frequency:

A(f) = 1 for f <= f 0 (43a)

A(f) = 0 for f 0 < f (43b)

In contrast, a **high-pass filter** lets all higher frequencies pass and keeps the low ones:

A(f) = 0 for f < f 0 (44a)

A(f) = 1 for f 0 < f (44b)

In reality, however, we do not achieve such sharp characteristics with ideally steep edges, therefore an important property of filters is their steepness, most often indicated by the number of decibels per octave; so, for example, a high-pass filter with an attenuation of 6 dB/oct will reduce the voltage amplitude of a signal with a frequency of half the cutoff frequency of the filter to approximately half, with a frequency of a quarter to a quarter, etc.

Simple Electrical Filters

As a simple filter for one frequency, we can use an LC circuit , composed of a coil and a capacitor. Instead of high-frequency and low-frequency filters, we can use combinations of resistors and capacitors (RC circuits).

A simple RC filter, connected as a low-pass filter , passes low frequencies, while high frequencies are attenuated with a slope of 6 dB/oct. Such a filter is also called an integrating element , because the voltage on the capacitor is given by the integral of the current with which it is charged. On the other hand, a simple RC filter connected to a high-frequency filter passes high frequencies and attenuates low frequencies with a steepness of 6 dB/oct. Such a filter is also called a derivative cell , because the current passing through the capacitor is proportional to the derivative of the voltage applied to it.

In both cases, we are interested in the cut-off frequency at which the effect of the given filter begins to manifest itself (the amplitude characteristic begins to decrease to one side or the other). We calculate this frequency as the reciprocal of the time constant of the RC cell:

f 0 = 1 / τ[Hz; with](45)

We calculate the time constant as **the product of resistance and capacitance**

$\tau = R.C[s; \Omega, F]$(46)

We will understand the physical meaning of the time constant if we consider the given cell as a transmission system, to the input of which we apply a step **input voltag**e and we monitor the course of the voltage at its output. In both cases, the output signal will have an exponential course. In the case of an integrating cell, the output voltage will rise according to the relationship

$u \text{ height } (t) = U. (1 – \exp(-t/\tau))$(47a)

i.e. during the time $t = \tau$ it rises to 1 – 1/e (i.e. 63%) of the input voltage value.

In the case of a shunt cell, the output voltage will decrease according to the relationship

$u \exp (t) = U. \exp(-t/\tau)$(47b)

i.e. during the time $t = \tau$ it drops to 1/e (i.e. 37%) of the input voltage value.

The jump voltage is generally used as a **calibration signal** for examination devices (EKG, EEG and others). The output signal is written on paper or displayed on the screen. From the course of the curve, we can then infer the course of the transmission characteristics of the entire device (as we discussed in section 2.5), or estimate and verify the settings of the filters.

Power Amplifiers, Recording Devices

After the output from the filters, the biosignal in traditional devices is amplified by power (or output) amplifiers , the output of which has sufficient power to move the stylus in the recording device. The recording device is traditionally made up of a cylinder with rolled-up raster paper and a mechanism that moves the paper at a constant speed in one direction (out of the device). Pens move along the paper in a direction perpendicular to the paper's direction of movement, whose instantaneous deflection corresponds to the instantaneous size of the biosignal in the respective channel (the number of pens is usually the same as the number of channels). With this procedure, the time-varying biosignals are recorded on moving paper and a graph of the corresponding function is drawn there. Thus, the time-varying signal is fixedinto a time-constant curve on paper and can serve as a template for evaluation by the relevant specialist.

The scales of all axes of the graphs displayed are important . The time (usually horizontal) axis is common to all graphs and is given by the speed of paper movement. **The time interva**l between two events captured on the paper strip, measured in seconds, is obtained by dividing this distance, measured for example in mm, **by the speed of the paper shift** , given in mm/s. For convenient reading, the rasterization of the paper already corresponds to certain round time intervals.

Because, for historical reasons, each investigation method uses its own standard paper advance speeds, the relevant papers are also rasterized differently and it is not a good idea to mix them up, even if they happen to be dimensionally mixed. So, for example, while in an ECG examination the basic speed of the paper is 5 cm/s and the derived speeds are double or half, the basic speed of the EEG is 3 cm/s. Therefore, the time grid for ECG and EEG paper must also be different.

The sizes of the observed biosignals are an independent variable on the recorded graphs. However, their displayed size depends on the set total amplification and on the characteristics of the pens. Therefore, it is often necessary **to calibrat**e the device before examination (or at least occasionally) , i.e. when introducing **a calibration** (usually rectangular) **signa**l of known size, check how it appears on paper. It should also be noted that while the time scale is in principle common to all curves, their voltage and other **scales may differ from each othe**r .

In the case of electrical biosignals, the gain constant is usually given in mm/mV or mm/mV. In the case of other than electrical biosignals (e.g. during polygraphic recording), this conversion constant is then given in the appropriate units – e.g. when sensing pressure, it will be e.g. torr/mm, Pa/mm, etc.

In recent years, the recording of biosignals on paper is increasingly giving way to the so-called paper-less method of recording, where a personal computer, equipped only with some appropriate input device, is often used to monitor biosignals. The following chapter deals with the problem of how an analog signal is converted into a digital form. As for the output, the biosignal is usually displayed directly on the computer screen and, if necessary, it can also be printed on the computer printer. It might then seem that the chapter on recording on paper is already out of date. This is not the case, because the principles mentioned here are also preserved for all other imaging methods, and moreover, the recording of biosignals on moving paper is the easiest to imagine from a pedagogical point of view.

Signal Digitilisation

Until now, we have dealt with analog transmission and signal processing, when the transmitted signal changed continuously throughout the chain and each value of the signal corresponded to some value of some physical quantity. This method was practically the only possible technical solution for most industrial and medical devices until the 1960s, and it is still often encountered today in many older EEG and ECG devices, which record waveforms

on a paper strip. Practically all modern devices already use the advantages of computerized (numerical, i.e. digital Latin digit = finger meant counting on the fingers, in today's meaning of the word English digit = number) processing of biosignals.

However, this does not mean that everything we have said about the analog method of transmission has only historical value today - on the contrary: even in every modern device, the input biosignal must first be processed in an analog way and only at a certain stage can it be digitized, i.e. converting the signal from its continuous (analog) to discontinuous (digital) form. in this form, the investigated signal is no longer represented by the value of some physical quantity, but by a series of numerical values. (We can say that the degree of abstraction is higher, one physical quantity is not represented by another physical quantity, but by numbers.)

This conversion is provided automatically in modern devices using so-called A/D converters (i.e. analog/digital). (The opposite conversion of the digital signal to analog is performed by D/A, i.e., digital-to-analog converters, for a change.) In the case of a slow analog signal, we can also perform the A/D conversion manually - for example, a nurse who measures a patient's temperature twice a day works in this case like a slow A/D converter. You will also proceed in a number of physical practice tasks by subtracting the magnitude of some measured quantities and writing the values in numerical form into tables - again a case of manual A/D conversion. Another example of manual A/D conversion is reading a quantity from a graph.

Then digital processing will follow, i.e. performing some mathematical operations with the values in the tables. You can then plot the measurement results on a graph - i.e. you perform D/A conversion again - for example in task No. during audiogram examination. If, instead of counting with numbers, you calculate using a nomogram - e.g. problem no. – body surface determination – you are doing de-facto analog processing, as opposed to digital. They are good examples to illustrate the concept of A/D and D/A conversion and digital and analog processing.

The basic principle of A/D conversion is the same for manual and automatic conversion: the main concepts are signal sampling and quantization .

Sampling

In classical physics, in the field of which we are moving, we assume that time flows uniformly continuously, i.e. we can mark each instant of time with some value t[s], where t is a real number. Then, however, in the finite interval <t1, t2> lies an infinite number of time instants t, to which an equally infinite number of functional values f(t) correspond, also in the field of real numbers. These assumptions can be useful if, for example, we have previously specified the course of some signal in analytical form. However, if we obtain data in an experimental way, for example during the examination of a patient, then we get each functional value as a result of measuring some quantity. Although we no longer have to perform a series of such measurements one after the other in a manual way as in the past, but automatically, each individual measurement of some quantity at one point in time requires some, albeit minimal time. In order to be able to measure the value of some constantly changing quantity, we have to "stop" it for a moment - in other words, take a sample at a certain point in time for further processing.

Like when a nurse takes a thermometer or a blood sample from a patient. Such a sampling circuit, which is able to take a sample of a changing signal at some point and hold its value for a short moment, can be schematically imagined as an integrating RC circuit, connected by a switch to the measured signal. However, the time constant of the RC circuit must be much smaller than the switching time - in that case, the capacitor just needs to be charged to the voltage corresponding to the monitored signal. After opening the switch, the capacitor will hold the signal value at a constant level for the duration of the A/D conversion.

Only in the next phase can the actual A/D conversion take place. This process is usually repeated periodically with a frequency that we call the sampling rate . The maximum achievable sampling frequency is determined by the design and quality of the A/D converter used and it is obvious that it cannot be higher than 1/T, where T is the total time required to convert one sample.

The A/D converter can either work with the maximum possible sampling frequency, or we can usually set a lower sampling frequency. Determining the optimal sampling frequency is a very important decision that can significantly affect the entire further measurement: Setting a too low sampling frequency may not only lead to less accurate results, we may even get completely meaningless results.

Let's imagine that we sample a 50 Hz sinusoidal signal with a sampling rate of 50 Hz: in that case we will take the sample each time at the same phase of the signal's waveform and therefore measure the same value each time; the result will be a constant value, instead of AC voltage we will measure DC voltage! What happens if we try to improve the situation and increase the sample rate to 60 Hz? The result will be that we measure an alternating signal with a frequency of 10 Hz! Further increasing the sample rate to 70 Hz, we measure a 20 Hz signal, etc., until only at a sample rate of 100 Hz - if we're lucky - we have a chance to measure the actual 50 Hz. But what happens to the measured amplitude? Just in case we happen to "hit" each other and sample the signal in moments, when it acquires the highest positive and lowest negative values, we have the opportunity to measure its real amplitude. In other cases, the measured amplitude will be lower, and if we happen to "hit" moments when the signal passes through zero, we will still only measure zero. And if we increase the sampling frequency to 110 Hz, instead of a constant amplitude AC signal, we will measure a 50 Hz signal that will be amplitude modulated by a frequency of 10 Hz! Try to imagine or paint all the mentioned cases. Only then will we clearly see how the correct choice of sampling frequency can drastically affect the results of the entire measurement. instead of an alternating signal with a constant amplitude, we will measure a 50 Hz signal, which will be amplitude modulated with a frequency of 10 Hz! Try to imagine or paint all the mentioned cases. Only then will we clearly see how the correct choice of sampling frequency can drastically affect the results of the entire measurement. instead of an alternating signal

with a constant amplitude, we will measure a 50 Hz signal, which will be amplitude modulated with a frequency of 10 Hz! Try to imagine or paint all the mentioned cases. Only then will we clearly see how the correct choice of sampling frequency can drastically affect the results of the entire measurement.

According to the so-called **Shannon-Kotělnikov** theorem, the sampling frequency must be at least twice as high as the highest frequency included in the spectrum of the sampled signal (see section 1.4 on the Fourier transform). However, as we saw in the given example, even double the frequency may not be a guarantee of error-free measurement, so in practice an even higher sampling frequency is chosen . In addition, in the analog part of the chain, we must use a **low-frequency filter** (see section 5.7 on filters) to guarantee that there are no components of higher frequencies in the monitored signal: such components would not only not be displayed correctly, but would also disturb the entire measurement - they got we would artifacts due to **inappropriate A/D conversion** .

It might seem that the higher the frequency, the better, but we have to realize that with ten times the sampling frequency, we will get ten times more measured values, which will have to be stored in the computer's memory and further processed. It can then happen that an inappropriately high sampling frequency can slow down the entire process to such an extent that it seriously disrupts its flow. The resulting choice of sampling frequency is therefore always the result of some compromise, given by the characteristic properties of the observed signal, the technical possibilities of the technique used, the purpose of the measurement, the experience of the experimenter, or the result of several trials and errors.

Quantization

Any measurement in which some measured quantity is calculated takes place with a certain, not unlimited, accuracy. If we have a two-meter available to measure lengths, with which we are able to read off individual measurements, then the result of measuring any length using this two-meter will be, for example, an integer in the range from 0 to 2000, expressing the measured length in millimeters. Or, for example, a decimal number in the range from 0.00 to 20.00, expressing the measured length in dm. This applies whether we measure the diameter of a circle or its circumference. At the same time, we know that if the diameter of a circle is given by a rational number, its circumference will be expressed by an irrational number according to the relation o = p d. However, as a result of the measurement, we are always able to obtain only rational numbers - in the usual expression, decimal. Mathematically, we can express this as mapping the set of irrational numbers into the set of rational numbers.

This situation, well understandable from everyday life, occurs whether we measure length, electric voltage or any other quantity with any gauge, device, analog (hand) or digital (digital). When measuring a continuously variable (for example, linearly increasing) voltage with an A/D converter, this means that at the output of the converter (in a graphical representation) instead of a straight continuous line, we receive a discontinuous, step-like broken line. At the same time, the heights of the steps correspond to the voltage levels that the A/D converter can distinguish. Unlike the common meters and devices that we are used to, A/D converters work mostly in binary (two) code; the number of distinguishable levels is then expressed by the appropriate power of two. For example, an eight-bit A/D converter can only distinguish 2 8 = 256 levels, a twelve-bit 212 = 4096 levels. In this last case, the individual levels will be 1/4096 of the total range of the transducer. If the input range runs from -5V to +5V, then the individual steps of the transfer characteristic will have a height of 10V/4096, i.e. approximately 2.5 mV.

The common **consequence of sampling and quantizin**g the signal is that after its digitization we can no longer (theoretically) draw the originally continuous curves continuously, but we can imagine the given situation as if we were drawing them on squared paper and at the same time we could only wrap the sides of these squares - the resulting curves will come out slightly "bony". In order to reduce this non-linear distortion of the signal caused by A/D conversion to a minimum, it is necessary to set and use the range of the converter as best as possible - in addition to the already mentioned sampling frequency - **with regard to the fluctuation** of the sensed signal. The problem arises if the dynamics of the processed signal varies within wide limits.

Let's take sound digitization as an example. Let's imagine that we would like to use such an A/D converter that would be able to handle sounds in the same intensity range as the human ear. It will be enough for us to quantize the weakest signal, corresponding to the threshold level of 0 dB, with the coarsest possible resolution of one bit, i.e. to only two levels. How many voltage levels will the converter have to have in order to be able to process even a signal corresponding to a pain level of 120 dB? The number of decibels, expressing the ratio of two voltages, is calculated from the relationship 20 log (U/U 0), from which it immediately follows that the given converter would have to have two million levels, i.e. 21 bits, which would be a very difficult device to manufacture even in today's advanced times. The comparison well illustrates how modern technology hardly reaches parameters comparable to the natural possibilities of our organism.

Multiplex

Earlier we mentioned that the vast majority of sensed biosignals are actually **vector in nature** . In practice, this means that each scanned channel must have some electrodes, converters and especially pre-amplifiers, filters, amplifiers, etc., ensuring sufficiently high-quality analog transmission of the signal up to the point of its digitization. In principle, a possible but expensive solution is that each channel is equipped with its own A/D converter. A cheaper solution assumes that voltages from all measured channels are successively fed to one complete A/D converter during a single sampling interval. Digitized signal values of all channels then gradually appear at the output of the converter. We call the mentioned solution a (time) multiplex. However, the price we save on the number of A/D converters used is paid by a proportional **reduction in the sampling frequency** (it decreases at least as many times as the number of channels we multiplex.)

Roles of Biophysics Practitioners

Electrocardiography (ECG) [edit | edit source]

The ECG is a standard non-invasive method of functional examination of the electrical activity of the myocardium. Unlike CNs, the work of the heart shows much greater synchronicity and periodicity. The signal spreads relatively easily from the myocardium in all directions throughout the body without being significantly weakened. We can therefore record an ECG signal with a relatively large amplitude (units to tens of mV) practically at any point on the body surface. The relative ease of obtaining an ECG examination predisposes it to the place of a suitable candidate for the first introduction to the principles of examination of electrical biosignals. For these reasons, ECG examination is included among the tasks of a biophysical practitioner.

Origin and course of the ECG signal [edit | edit source]

The impulse for myocardial contraction originates in the so-called sinoatrial (SA) node in the region of the right atrium, from where it spreads further. For a detailed description, we refer to the available literature. For the purpose of our brief explanation, it is important to note that this primary signal is so weak that it is virtually undetectable in a normal ECG recording. The first wave of the ECG recording that we can see on the ECG recording is the P wave, which indicates the depolarization of the atria, i.e. their starting contraction. We are no longer able to recognize the repolarization of the atria on the ECG either, because the relevant biosignal is overshadowed by a much higher signal coming from the depolarization of the ventricles; this signal is characterized by a complex of QRS waves. The following T wave indicates the subsequent repolarization of the ventricles. It is not within the competence of a first-year biophysics student to deal in detail with the interpretation, physiology or pathophysiology of an ECG,

Einthoven (bipolar) leads [edit | edit source]

Historically, electrocardiography was introduced as a clinical method in 1906 by the Dutch doctor EW Einthoven (read: Einthofen). He recorded the ECG signal in humans with a string galvanometer between the upper limbs, for the ease of connecting the electrodes to the wrist. The measured signal then corresponds to the potential difference between the two electrodes, therefore it is a bipolar connection. If we mark the right hand with the letter R (right, marked in red by default) and the left L (left, yellow), then the LR signal is called I. Einthoven's lead . Later, another electrode was attached near the ankle of the left leg F (foot, green) and thus the possibility to measure the potential difference FR (II. Einthoven's lead) and FL (III. Einthoven's lead). The N electrode (neutral – black) is not included in the actual sensing and serves only as grounding. ("Only" does not mean that it would be possible to omit it with impunity, because then the measurement would be disturbed by various disturbances and there would be a risk of damage to sensitive input amplifiers.)

Cardiac axis vector [edit | edit source]

What is the significance of monitoring a signal from one source (the myocardium) taken from several electrodes at the same time? We can imagine that the summation potential of all myocardial cells creates a kind of electric dipole in space , which changes its direction and size during the heart period. We call this imaginary vector the electric heart axis vector. Because it changes over time, its magnitude and direction differ at the moment when the different waves of the ECG record reach their maximum. The largest and most important is the direction of the electrical cardiac axis vector for the R wave.

Einthoven's triangle [edit | edit source]

If we now imagine bipolarly connected Einthoven leads I, II and III as sides of an equilateral (so-called Einthoven) triangle, at the vertices of which electrodes R, L and F are located, then we will have a coordinate system of three axes, rotated by 60 degrees to each other (we also count the opposite directions of the axes), into which the vector of the heart axis is projected. According to the polarity and size of the individual waves of the ECG recording in the individual leads, we can then calculate, or at least at first glance estimate, the rotation of the electric heart axis vector. So, for example, if wave R appears highest in II. lead, then we can estimate that the electric heart axis vector lies approximately in the direction of the side of the Einthoven triangle, representing II. lead, i.e. in the downward right direction (when looking towards the patient). This is approximately the normal (usual) inclination of the heart's electrical axis. The direction horizontally to the right indicates 0 degrees, and angular degrees are measured from this direction in a clockwise direction, and therefore direction II. of the channel corresponds to the inclination of the heart axis +60 degrees. We refer to deviations from the norm asturning the electric axis to the right or left .

Godberg (unipolar) leads [edit | edit source]

For better resolution, the Einthoven leads were later supplemented with other directions: By connecting the limb electrodes through resistances of the same size , a virtual center was created (the so-called Wilson clamp , see section 5.5 on unipolar connection), to which the reference inputs of three other differential amplifiers were connected. We can imagine the vectors of the new coordinate axes that have arisen as arrows, leading from the center (center of gravity) of the equilateral Einthoven triangle towards its vertices, representing the electrodes R, L, F; the newly formed leads were then named VR, VL and VF.

However, at this historical moment, electronic amplifiers were not yet used, so it was a drawback that the perpendicular bisectors of the triangle VR, VL and VF were shorter than its sides, and thus the received signal was also low. An improvement of this system was therefore a connection where the central point in the middle of the triangle was not created for all the electrodes, but for each reference point a point was created from two resistors

connecting the remaining electrodes. Geometrically, this means that the arrows of the vectors do not come from the center (center of mass) of the triangle, but from the centers of the opposite sides; therefore they are not the perpendiculars, but the altitudes of the triangle; their direction is the same, but their lengths, and thus also the size of the received signal, are 1/2 higher, therefore they are marked with the letter *a* as *augmented*, i.e. extended. In this way, we shed light on the designations of the corresponding leads still used today, such as aVR , aVL , aVF . We call them Goldberg leads , and unlike Einthoven's bipolar leads, where each lead represents a potential difference between two electrodes, these are unipolar leads, where each lead represents the potential of only one respective electrode.

Standard Limb Leads [edit | edit source]

By supplementing Einthoven's bipolar leads I, II, III with Goldberg's unipolar leads aVR, aVL and aVF, we obtain a total of 6 axes, rotated by 30 degrees , into which the vector of the electrical heart axis can be projected. Since all six leads shown are derived from the potential of the three limb electrodes, we call them the six standard limb leads . The plane in which the corresponding coordinate axes lie is roughly parallel to the surface of the table on which the examined patient lies on his back.

Thoracic leads [edit | edit source]

Over time, the need arose to investigate the movement of the electrical heart vector in space, i.e. it was necessary to place the electrodes in a plane as perpendicular as possible to this plane. This was achieved with the help of six electrodes V1 to V6, placed directly on the chest of the examined person so that electrodes V1 and V2 are located in the fourth intercostal space to the right and left of the sternum, further to the left is electrode V3 , and further still equidistantly placed electrodes V4 , V5 and V6 are located in the fifth intercostals: V4 in a line running through the center of the left collarbone, V5 in a line running through the anterior lash of the axilla and finally V6 in a line below the center of the axilla.

Heart Rate Variability

Heart Rate

An even simpler task than recording the course of the ECG curve in all twelve (six limb and six thoracic) leads, determining the inclination of the heart axis and possibly other parameters, is to determine the heart rate . To do this, we just need to choose a single lead on which the QRS complexes will be clearly visible. The distance of the spiky waves R, belonging to two consecutive beats, is called the RR interval . The heart rate (in Hz) is then the reciprocal of the RR interval; after multiplying by 60, we get the number of beats per minute.

HRV Baroreflex

We can then use the unused EEG channel to register some other biosignal, for example the course of breathing. By carefully examining both simultaneously recorded biosignals, we can find that the heart rate changes depending on the breathing phase of the examined person . This dependence is determined physiologically by the periodic stimulation of the vegetative nerve, which controls the heart rate, during the breathing cycle (so-called baroreflex). By investigating this dependency, we can therefore obtain important information about its proper function. It has been proven, for example, that blocking this function, for example, during extreme long-term overloading of athletes (especially football players), can lead to their sudden death, which was previously unexplained. Regular examination of heart rhythm variability (HRV= Heart Rate Variability) of leading athletes should therefore already be a matter of course today.

Breath registration We can register the breath using various mechanical transducers, as we showed in section 5.2.1, or also using a thermistor, see 5.2.3.

Pulse wave velocity investigation

When examining the pulse wave, we correlate the recording of the heart's electrical activity with the course of pressure or blood flow at the distal end of the peripheral artery. In this way, it is possible to calculate the average speed at which the pulse wave propagates through the bloodstream. The obtained speed can be inserted into the hydrodynamic model and from it, for example, the modulus of elasticity of blood vessels can be determined. This is an important circulatory parameter, which can indicate the biological age of the circulatory system, its involvement with atherosclerotic changes, etc. The course of such biosignals, such as monitoring the pulse on the finger, can be registered, for example, using a plethysmograph (registration of volume changes), changes in temperature, changes in absorption lights of different wavelengths (e.g. capnograph – changes in CO_2 concentration , oximeter – changes in O_2 concentration) etc.

The examination of heart rate variability and the examination of the pulse wave speed well illustrates the technique of polygraphic recording already mentioned above (see section 4.7), where we can record biosignals of different physical nature in different channels – here in one channel the electrical activity of the myocardium, in the other channel the movement of the chest during breathing, in further blood circulation of the finger, etc.

Blood pressure measurement

In medicine, we mean **blood pressure (BP)** as the pressure in the arteries, a value measured at the level of the heart or converted to this level. If we record the undistorted course of pressure changes by the direct method, we can subtract from the recorded curve both the maximum value during one beat - **systolic pressure (TKs)** and the corresponding minimum value - **diastolic pressure (TKd)** . We call the difference between TKs and TKd **the pressure amplitude (difference)** . **The mean pressure (TKm)** is the average of all the values that the pressure acquires during one pulse interval - it is not an arithmetic mean, but the mean value is closer to Tkd:

TKm = 2/3 TKd + 1/3 Tks(48)

In some sources, the mean pressure is indicated as BP with a stripe.

BP depends on cardiac output, the force with which blood is ejected from the left ventricle, peripheral resistance, the total amount of blood, and its viscosity. It is influenced by a large number of factors (age, gender, physical and psychological influences, daily rhythm, etc.).

The prescribed unit for BP is kPa. The World Health Organization (WHO) adheres to the torr unit (mm Hg bar) and gives the upper limit of normotension as 140/90 torr (= 18.7 / 12.0 kPa).

Blood pressure can be measured

a) **by a direct** (invasive) method, e.g. using a catheter connected to a membrane sensor, the pressure signal is converted to an electrical voltage and registered

b) **by an indirect method** , e.g. mercury or digital tonometer or Doppler scanning.

A mercury tonometer contains a reservoir of mercury, a measuring capillary with a scale in torr (and sometimes in kilopascals), a cuff with an inflatable balloon and a connecting tube. In some tonometers, the mercury reservoir can be closed. We wrap the cuff around the arm (the lower edge is about 2-3 cm above the elbow socket, the valve on the balloon is closed), and inflate it to about 180-200 torr. By releasing the valve, we let out the air slowly and continuously, and with the stethoscope placed above the brachialis artery in the cubit, we observe the so-called Korotkov phenomena (we hear them as gentle beats that gradually increase in intensity and then decrease again in intensity). At the moment of capturing the first Kf, we subtract TKs, the last audible Kf corresponds to TKd. We have to deflate the cuff completely before re-inflating it, because the remaining air causes stagnation of blood in the vessels (ie we increase TKd, so we don't measure the actual condition)! Another method is palpation of the pulse on a.

The examined person should be physically and mentally calm, in adequate microclimatic conditions. The arm must not strangle the sleeve.

Disposal of mercury waste: In the event that the reservoir is damaged and mercury is released, we collect the mercury in a closed container, preferably with a ground mouth (mercury vapors are toxic!). The rest of the mercury is sprinkled with powdered sulfur (sulfur praecipiatum), a chemical reaction creates vermilion (HgS) on the surface, which prevents evaporation. However, when touched, the ball "splits" into several smaller ones and sublimation resumes. Sulfur is suitable for sprinkling mercury, e.g. in parquet joints. On smooth surfaces, we cover the remaining mercury droplets with powdered zinc - this creates a solid amalgam that sublimes completely negligibly, is strong and can be swept away. The space must be sufficiently ventilated. We never combine dusting with sulfur and powdered zinc – the reaction is strongly exothermic!

Determination of Body Surface Area

Including the determination of the body surface among biosignals may cause wonder: what kind of biosignal is it? We have included this task in these scripts mainly because it is often performed together with blood pressure and ECG measurements in practices. However, with a little exaggeration, it is also possible to include the body surface among biosignals: it is a physical quantity characterizing the state of the examined organism, which changes over time - albeit slowly, but surely.

Determining body proportions is important for classifying an individual into different groups according to somatotype (leptosomal, mesosomal, pyknic). For accurate classification, it is necessary to measure the dimensions of various parts of the organism (e.g. body height, trunk length, limbs, width at the shoulders, dimensions on the skull, thickness of the skin fold in several places, body weight). During long-term monitoring of an individual, it is then possible to assess its development. Anthropology deals with monitoring these parameters in large population groups. These studies have several implications:

- determination of generally valid biological laws on the human organism, especially the laws of growth and development
- assessment of the health status and development of the individual, mainly during the period of growth and development
- knowledge of body proportions for industrial production (ergonomic aspects).

In practice, an individual's body height and weight are most often measured, from which the body surface is approximately determined using nomograms or by calculation according to a suitable formula, determined according to the average population. This quantity is then used to calculate optimal doses of drugs, or to recalculate physiological values (respiratory volumes, O 2 consumption and CO 2 output , energy balance of the organism, biochemical values) per 1 m 2 of body surface. We can come across values converted to the body surface of a standard individual, which is 1.73 m 2 . In addition, other corrections are mainly used in research, e.g. for active and passive body mass (fat tissue).

One of the methods of determining body surface area is calculation from the height and weight of the examined person according to the DuBois formula:

$P = H\,0.425\,.\,In\,0.725\,.\,71.84$ (49)

where P is body surface area in cm 2 , H is body weight in kg and V is body height in cm.

Alternatively, the result can be read from the nomogram, which was developed as a graphical aid for calculating the same formula.

Links

Source

- HEŘMAN, Petr. *Biosignály z pohledu biofyziky.* 1. edition. Petr Heřman – DÚLOS, 2006. 64 pp.

Recommended Reading

- AMLER, Evžen. *Praktické úlohy z biofyziky I.* 1. edition. 2006.
- HRAZDIRA, Ivo. *Biofyzika : učebnice pro lékařské fakulty.* 2. edition. 1990. ISBN 80-201-0046-6.
- KHAN, M. I. Gabriel. *EKG a jeho hodnocení.* 1. edition. 2005. ISBN 80-247-0910-4.
- KOMÁREK, Vladimír. *Dětská neurologie.* 1. edition. 2008. ISBN 80-7262-492-8.
- ROSINA, Jozef. *Lékařská biofyzika.* 1. edition. 2000. 0 pp. ISBN 80-902318-5-3.
- NAVRÁTIL, Leoš – ROSINA, Jozef. *Biofyzika v medicíně.* 1. edition. 2003. 398 pp. ISBN 8086571033.
- NAVRÁTIL, Leoš – ROSINA, Jozef. *Medicínská biofyzika.* 1. edition. 2005. ISBN 80-247-1152-2.