Action and Summation potential

Action Potential

Action potential (or nerve impulse) refers to a local, short-term, significant change in the membrane potential that spreads along the cytoplasmic membrane of the cell in one direction. We most often talk about the action potential in connection with the membrane of nerve and muscle cells. A rapid change in the membrane potential (of the order of 100 mV) is made possible by the so-called resting potential present on the membrane at rest, by the difference in the concentration of ions mainly Na + , K + and Cl - inside and outside the cell and by the presence of numerous voltage-controlled channels for Na + and K + ions. The action potential is important primarily in neurons for the propagation of information along axons over long distances and in muscle cells and fibers to control voltage-gated Ca 2+ channels and enable muscle contraction.

Voltage-gated ion channels

Ion channels are penetrating membrane proteins that allow the passage of charged particles (mostly Na + , K + , or Ca +) through the cell membrane. Specifically, voltage-gated ion channels react very sensitively to changes in the membrane potential and when it is reduced or depolarized, they change their conformation very quickly. By this mechanism, they can change their permeability to ions by several orders of magnitude in fractions of milliseconds. Ion channels are highly selective mediators of transmembrane transport. The probability that a cation of another element would pass through a specific ion channel is close to zero. Sodium channels react very quickly even to a relatively weaker decrease in negative charge (membrane potential around -55 mV) on the inner side of the membrane. Potassium channels only respond to a very positive charge inside the cell and open and close more slowly. This is of great importance during membrane repolarization when the sodium channels are already closed, however, potassium still releases potassium cations out of the cell after a drop in concentration. It is important to realize that the diffusion of positively charged ions along a concentration gradient is a passive event and therefore does not require the supply of energy in the form of ATP or carrier proteins.

Membrane and resting potential

This is the difference in electrical voltage on the inside and outside of the cell's cytoplasmic membrane under physiological resting conditions. It is determined by the different concentration of ions of various elements outside and inside the cell. We find large differences in the concentrations of Na + , K + , Cl - and especially Ca 2+ ions , as well as in the concentrations of negatively charged proteins, see table.

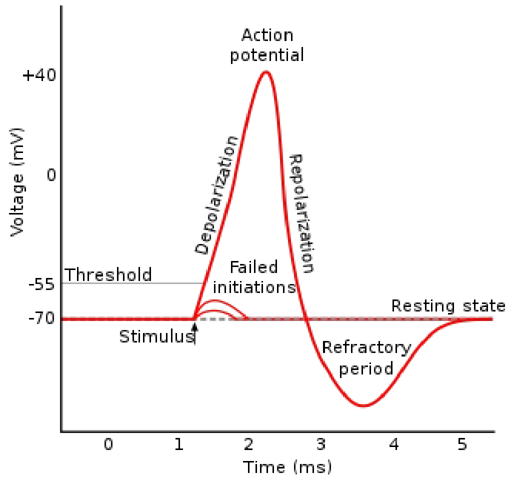
Ion	Intracellular concentration [mmol/l]	Extracellular concentration [mmol/l]
Na^+	12	145
K^+	155	4
Ca^{2+}	10^{-8} až 10^{-7}	2
Cl^-	4	120
HCO_3^-	8	107
Proteins (A^-)	120	0

We can therefore understand the membrane potential as an equilibrium relationship between the concentrations of charged ions inside and outside the cell. Differences in concentrations are mainly caused by the different permeability of the membrane for different ions. For example, there are ion channels for both K + and Na + , but they are closed under resting conditions, large protein and negatively charged molecules are not able to pass passively through the membrane under physiological conditions despite the attractive forces acting on them due to their electrical charge from outside the cell. Of the active mechanisms maintaining the concentration gradient of ions, the transmembrane transporter Na + /K + ATP-ase , which transfers 3 Na + ions when ATP is consumed , probably plays the most important role into the extracellular space in exchange for 2 K + ions transported into the cell. The resting membrane potential of most cells in the body ranges from -30 to -90 mV, with the inner surface of the cytoplasmic membrane carrying a negative charge and the outer surface carrying a positive charge. Neurons and elements of muscle tissue make a great effort to maintain this membrane potential around -70 to -90 mV.

Action potential phase

thumb|Action potential

- **1. Stimulation and formation of an action potential (membrane depolarization)**



Action Potential

Several conditions must be met for an action potential to occur. Above all, the membrane potential must rise from the standard approx. -75 mV to a value of around -55 mV, so that the percentage of open voltage-gated sodium channels creates a sufficient flow of cations into the cell. The fulfillment of this condition depends on the number and strength of positive and negative stimulations at synapses with other neurons and on the summation of these stimuli on a specialized part of the axon called the initial segment. Neither the length nor the strength of the stimulation has an effect on the subsequent amplitude of the action potential, but it has an effect on the latency between the reception of the stimulus and the generation of the action potential and the frequency of the generation of action potentials (longer and stronger stimulation causes a greater number of action potentials that arise more frequently and faster). The formation of the action potential therefore takes place according to the " all or nothing " doctrinetherefore, potassium begins to flow out of the cell already at this stage, thus restoring the original membrane potential. However, the huge amount of open sodium channels outweighs this effect. At the end of this phase, the rate of depolarization begins to decrease, because the concentrations of sodium cations near the inner and outer surfaces of the membrane are already almost equalized, and there is slowly a significant permeation of potassium out of the cell due to the increasing number of open potassium channels. The time from the beginning of the stimulus to the emergence of a strong action potential (i.e. the time of the first phase) can be very variable and depends on many factors (stimulus intensity, type of cell producing the action potential, temperature, concentration of ions in the intracellular and extracellular space, etc.). However, it is usually less than 1ms. At the end of this phase, the rate of depolarization begins to decrease, because the concentrations of sodium cations near the inner and outer surfaces of the membrane are already almost equalized, and there is slowly a significant permeation of potassium out of the cell due to the increasing number of open potassium channels. The time from the beginning of the stimulus to the emergence of a strong action potential (i.e. the time of the first phase) can be very variable and depends on many factors (stimulus intensity, type of cell producing the action potential, temperature, concentration of ions in the intracellular and extracellular space, etc.). However, it is usually less than 1ms. At the end of this phase, the rate of depolarization begins to decrease, because the concentrations of sodium cations near the inner and outer surfaces of the membrane are already almost equalized, and there is slowly a significant permeation of potassium out of the cell due to the increasing number of open potassium channels. The time from the beginning of the stimulus to the emergence of a strong action potential (i.e. the time of the first phase) can be very variable and depends on many factors (stimulus intensity, type of cell producing the action potential, temperature, concentration of ions in the intracellular and extracellular space, etc.). However, it is usually less than 1ms. because the concentrations of sodium cations near the inner and outer surface of the membrane are already almost equalized and there is slowly starting to be a significant permeation of potassium out of the cell due to the increasing number of open potassium channels. The time from the beginning of the stimulus to the emergence of a strong action potential (i.e. the time of the first phase) can be very variable and depends on many factors (stimulus intensity, type of cell producing the action potential, temperature, concentration of ions in the intracellular and extracellular space, etc.). However, it is usually less than 1ms. because the concentrations of sodium cations near the inner and outer surface of the membrane are already almost equalized and there is slowly starting to be a significant permeation of potassium out of the cell due to the increasing number of open potassium channels. The time from the beginning of the stimulus to the emergence of a strong action potential (i.e. the time of the first phase) can be very variable and depends on many factors (stimulus intensity, type of cell producing the action potential, temperature, concentration of ions in the intracellular and extracellular space, etc.). However, it is usually less than 1ms.

- **2. Peak and phase of repolarization**

The moment when the sodium channels are maximally open, the maximum amount of sodium cations has been transported and the membrane potential has reached its maximum value, we refer to as the so-called "peak", which can be loosely translated into Czech as the "peak" of depolarization. In this phase, however, the same increase in membrane potential, which initially

opened the sodium channels, begins to close them slowly and relatively long-term (inactivation of voltage-gated sodium channels). On the contrary, the number of open channels for the transport of K + increases very quickly , which causes an increasingly intense diffusion of these cations out of the cell. The resulting combination of sodium channel closure and potassium channel opening causes a rapid drop in membrane potential to its original value of around -70 mV.

- **3. Hyperpolarization of the membrane**

  The large increase in membrane potential in the first two phases opened a huge number of potassium channels. The problem is that some of these channels do not close immediately after reaching the resting potential. This usually results in a phenomenon referred to as membrane hyperpolarization, during which the membrane potential drops to values around -100 mV. Once all the potassium channels are closed, the membrane potential returns to -70 to -90 mV.

- **4. Refractory phase**

  The period in which the re-emergence of an action potential cannot occur regardless of the strength of the stimulation is referred to as the refractory phase. This phenomenon is caused by the inactivation of sodium channels during phase 2 and usually lasts only a few milliseconds after the onset of the action potential. This property of sodium channels is also of great importance for the propagation of the action potential along the axon, as it prevents the propagation of the signal in the opposite direction that would occur without long-term inactivation.

During all these phases, the highly different concentrations of cations in the extracellular and intracellular spaces are restored at the same time. The so-called Na + /K + ATP-ase has the greatest merit in this process, transferring 3 Na + ions to the extracellular space in exchange for 2 K + ions transported into the cell during ATP consumption. The activity of this enzyme is not required in bursts, since each generation of an action potential means the movement of only about 1/100,000 cations.

Action potential propagation

The main limiting factors for the propagation of a digital signal (which is essentially what an action potential is) tend to be the speed of propagation, the maximum frequency of signal changes per second, and the loss of signal strength and quality along the way. The action potential propagates along the axon without loss (no decrement) due to continuous active amplification. The maximum frequency of evoking action potentials on the axon is around 30–50 Hz, but can reach up to 500 Hz. The speed of signal propagation along the axon is very variable in the human body and ranges from 0.1 m/s to 120 m/s. Myelination of the axon has a major influence on the speed of propagation.

- Saltatory Method of Propagation

It only applies to myelinated axons. The signal does not propagate continuously along the axon membrane, but jumps between individual Schwann cell nicks of Ranvier. This method of signal propagation causes, in addition to an increase in the speed of signal propagation, a significant reduction in the energy demand of the entire process, which is very significant when it comes to the energy consumption of the human nervous system (approx. 20% of the total energy expenditure).

Summation potential

The action potential itself can only be investigated in laboratory conditions on in vitro preparations, where we have the means for sufficiently fine and accurate sensing of the signal from the intracellular space of a single cell. The next level, the action potentials of the motor unit, can be captured during an EMG examination with a fine needle electrode (it picks up signals from an area of the order of a fraction of a mm 3).

In routine diagnostics, we monitor action potentials at the level of tissues or organs and talk about the so-called summation potential. The summation potential originates from the whole organ, not from 1 cell like the action potential. The sensed biosignal is a weighted sum of action potentials from a number of different cells that spread through the extracellular space - in this case we can imagine it as a number of electrical resistors. From such a model, we can derive the resulting biosignal as an approximate weighted arithmetic sum of the signals of individual cells.

Weighting principle: The signal from closer cells will be captured with a greater amplitude compared to the attenuated signals of more distant cells - there is a significant dependence of the weight on the distance and the signal does not spread far, hence "near field". On the other hand, the ECG signal spreads from the myocardium to the whole body without noticeable attenuation - its amplitude will be practically the same whether it is taken, for example, from near the shoulder or the wrist. In this case, the scales are balanced and the potentials spread through the body over a long distance without noticeable attenuation, hence "far field". The result of potential weighting is that the measured values of the summation biosignals are not an order of magnitude higher than the amplitudes of the action potentials that cause them.

Special example: An electromyogram read by a surface electrode is a typical summation potential, where a number of signals from a large number of cells overlap. Its frequency spectrum is in the range of hundreds to thousands of Hz. Such a strong signal cannot be directly written down on paper, so the doctor watches it on the screen or it is possible to convert it into an acoustic signal.

The use of summation potentials in medicine

Electrodiagnostics deals with the registration of electrical potentials arising from the activities of excitable organs and tissues during diagnostic examinations. We can observe the record of potential changes over time not only on the membrane of cells (muscle, nerve), but also on the surface of the body, either in a unipolar or bipolar arrangement. Unipolar arrangement – 1. electrode attached to the given tissue, 2. reference electrode with constant potential. Bipolar arrangement – both electrodes active, applied to different places of the same tissue.

Diagnostic methods using the evaluation of summation potentials:

Examination name	Abbreviation	The goal of the examination
electrocardiography	EKG	cardiac action potentials
electroencephalography	EEG	brain action potentials
electrocorticography	ECoG	brain action potentials
electromyography	EMG	muscle action potentials
electrogastrography	EGG	gastric smooth muscle potentials
electroretinography	ERG	retinal action potentials
electrohysterography	EHG	uterine action potentials

Sources

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