



How Brain Cells Work. Part II

The Action Potential

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Animation and Art: André Malavazzi

Electricity is a natural phenomenon in our body and it is involved in the specific functions of certain special cells in the brain and in smooth and striated muscles. Each pattern of light, sound, heat, pain, each twinkle, finger snap, each thought translates into a sequence of electric pulses. How does it happen?

Nerve cells possess properties similar to other cells in many aspects: they feed, breed, undergo processes of diffusion and osmosis in their membranes and so on, but they differ in a major aspect: they process information. The ability of nerve cells to process information relies upon the special properties of the neuron membrane, which controls the flow of substances to the inner cell (sodium, calcium and potassium ions and so on).

Neurons do not exist in isolation: they also connect themselves to each other, forming the so-called neural chains, which transmit information to other neurons or muscles. The nerve impulses propagate throughout these chains. Two kinds of phenomena are involved in the nervous impulse: electric and chemical. The electrical events propagate a signal inside a neuron, and the chemical events transmit the signal from one neuron to another or to a muscle cell. The cell contact or junction between one neuron and the next, or between a neuron and a muscle cell is called **synapse**, which will be dealt with in future articles.

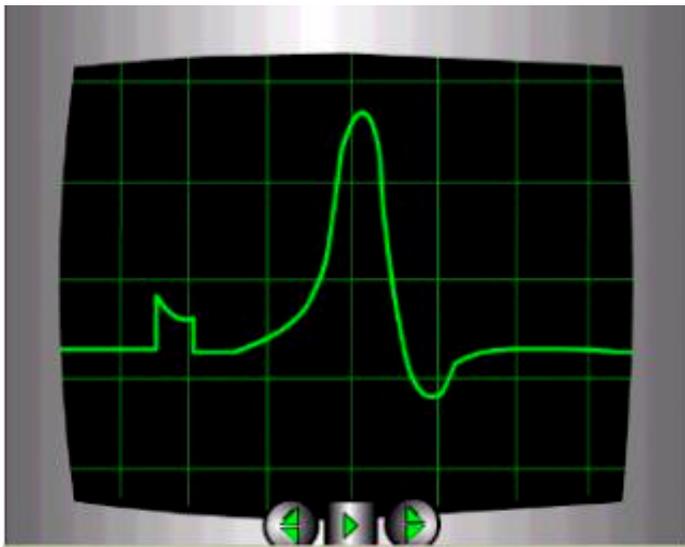
The nervous impulse

A nervous impulse is the transmission of an electric change along the membrane of a neuron beginning at the point of stimulus. The normal direction of the impulse in organism is from the body cell to the axon (see the article on the [structure of the neuron](#) on Brain & Mind issue # 7).

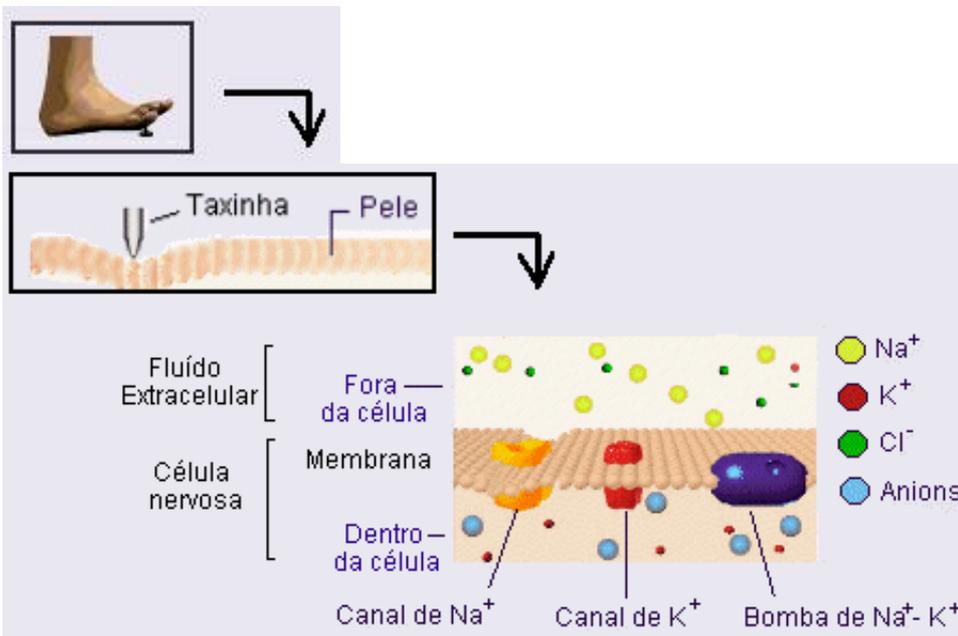
This nervous impulse or **action potential**, is a propagated, sudden and rapid change in transmembrane potential. Normally, as we have seen in the [previous article](#) in this series, the neuron membrane is polarized at rest, with a negative potential (-70 mV). The action potential consists of a rapid reduction of the negativity of the membrane to 0mV and the inversion of this potential to values up to some +30mV, followed by a very quick return to value somehow more negative than the potential at rest of -70mV.

The nervous impulse is known as action potential. The action potential is a phenomenon of electro-chemical nature and occurs due to the changes in the permeability in the neuron membrane. These changes in permeability allow the flow of ions from one side of the membrane to the other. Given that the ions are electrically charged particles, changes in the electric field generated by these charges take place.

One way we could visualize the action potential is by means of a thousand-fold electronic amplification of the electric changes captured by an electrode placed in contact with the neuron and representing the amplitude in volts, as a function of time, thanks to a piece of equipment called oscilloscope. On the screen on the left, the green line represents the evolution of action potential in a point in the neuron (from left to right). The initial straight line corresponds to the voltage of the resting potential of the membrane. The first alteration is an artifact caused by the beginning of electric stimulation. After a certain lag, the potential starts to increase (depolarization phase) and then to decrease (repolarization phase). After a short excess repolarization, the membrane potential returns to the value prior to stimulation. All these phenomena added up occur in just over two milliseconds.

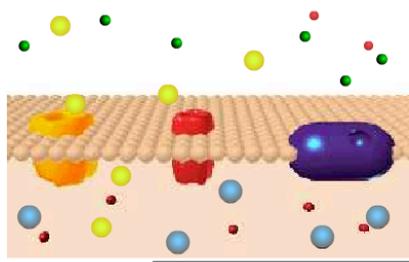


Potencial de ação exibido em um osciloscópio.

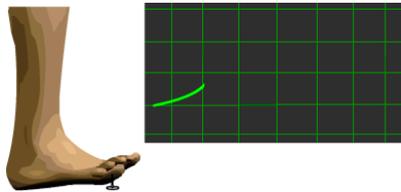


To imagine how the nervous impulse happens, observe the figure on the left. The perception of acute pain when a sharp object penetrates your foot is caused by the generation of certain action potential in some nervous fiber in the skin. It is believed that the membranes of these cells have sodium channels that open when nerve terminals of the cell are stretched. The initial chain of events is:

1. Sharp object penetrates the skin;
2. The membranes of nerve fibers in the skin are stretched;
3. Channels permeable to sodium (Na^+) are opened.



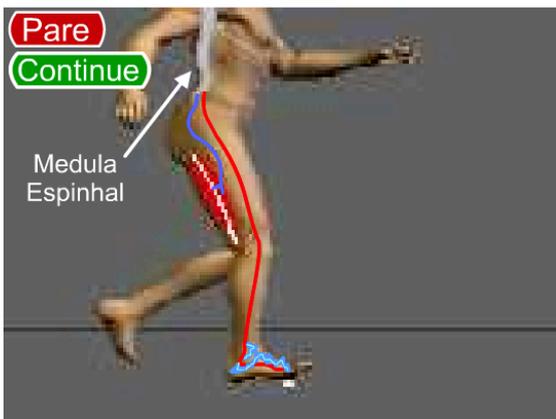
Due to the concentration gradient and negative charge in extracellular fluid, ions enter the fiber by means of these channels. Sodium entrance (yellow balls) depolarizes the membrane, that is, the side of membrane bathed by extracellular fluid becomes less negative in relation to the cell



interior. If this depolarization, called **generator potential**, reaches a critical point, the membrane then generates an action potential. The critical point of depolarization that must be overcome in order to fire an action potential is called **threshold**. The action potentials are caused by depolarization of the membrane above the threshold.

In the repolarization phase, the sodium channel is deactivated and the conductivity of membrane for potassium increases. These positive ions follow its chemical and electrical gradient and exit from the cell, thus gradually inverting the membrane potential (green balls)

In the recovery phase, the active sodium/potassium pump (blue channel in the figure) reestablishes the ionic levels which were altered during the action potential: for each sodium ion which is transported from the inside to the outside, a corresponding potassium is transported in the opposite direction.



The skin perforation is transduced into signals that travel upwards via sensory nerves (direction of information flow shown by arrows). This information arrives at the spinal cord and is distributed to interneurons (neurons that provide intermediate connections with other neuron chains). Some of these neurons send axons to the sensory region of the brain where the sensation of pain is registered. Other make synapses with motor neurons, which send signals downward to the muscles. The motor junctions command the muscle contraction and withdrawal of the foot.

This is an example of a neuron chain called **reflex arc**.

Fig.1.Simple Reflex - Human feet in contact with a tack (external stimulus). Medula espinhal = spinal cord; Para o Cérebro= to the brain

(Click on the button "Re-start" to see the animation).

How the Action Potential Works

Local or Generator Potential

As we have seen in the [previous article](#) of this series, the membrane of non-stimulated neuron (at rest) presents a difference of electrical potential between the interior and exterior of the cell of approximately 70 mV; a potential, which is maintained while the cell, is alive. This constitutes the potential of membrane potential at rest. How is it possible that the potential at rest can be disturbed up to generating an action potential?

When a stimulus is applied to the membrane, a temporary unbalance takes place between the electric charges of the membrane and the ions concentration in each side of the membrane, what is called a **local potential**. Whenever the membrane, starting at a potential at rest, is depolarized to around -50 mV, action potentials are generated. The potential that launches the action potential is called threshold (see figure above). At this threshold potential, the membrane is unstable. It spontaneously diminishes its polarity, very quickly and generally reaches an inversion of polarity: then follows a rapid increase (ascending curve) of the action potential that goes beyond potential zero and goes to an "overshoot". This state of diminishing charge, initiated at threshold levels, is spontaneous and progressive. It is also called an "excitation" The excitation has a short duration, normally less than one 1 ms (milisecond), being comparable to an explosion that rapidly dissipates itself.

A stimulus that tends to diminish the natural polarity of the membrane is called depolarizing stimulus. One stimulus that tends to increase the natural polarity is called polarizing stimulus. The local potential does not propagate, that is, it remains limited to the neighboring membrane at the local of the stimulus.

Properties of Generator Potentials

The local potential is very important to the functioning of the neuron. As we have seen in the chapter on [neuron morphology](#), the nerve cell has many short extension of cell body called **dendrites**. A neuron can receive simultaneously many depolarizing and hyperpolarizing stimuli coming from other neurons or from external sources of stimulation, in several parts of the dendrites and the cell body. Each stimulus generally provokes a small change in the local potential. When two local potential are very close (physically) they can "overlap" that is, there is a sum of their amplitudes). Or they can cancel each other, when they are in opposite directions. This is called a "**spatial sum**". It can happen also that two successive stimuli, separated from each other by a very short interval of time, occur at the same point in the membrane. Then, before the local potential caused by the first stimulus returns to normal, the second stimulus intervenes, either by summing or subtracting to the previous one. This is called a "**temporal sum**".

What the neuron does is a "summing up" of all local potentials. If the result is towards a major depolarization, from a certain threshold on, then a very important event takes place, which is the action potential. Let see why and how it occurs.

Initial Steps

When a stimulus reaches the membrane of the neuron, there is a small local depolarization. This stimulus can be of a photic, chemical, physical or pharmacological nature, depending on the sensibility of the cell. The depolarization provokes the opening of Na⁺ and K⁺ channels that are voltage dependent and allow the flow of ionic current from one side to the other side of the cell. Simultaneously there a flow of Na⁺ from the outside to the inside (as we have seen in the previous chapter, there is a higher concentration of sodium outside), which tends to further depolarize the membrane; and a flow of K⁺ from the inside to the outside that tends to repolarize the membrane.

"All or None"

There is, however, an important difference between Na⁺ and K⁺ channels: Na⁺ channels open much more rapidly than the K⁺ channels. Therefore, the depolarization causes a feedback effect: the more sodium enters the channel, the more it becomes permeable. It is like an avalanche of depolarization that eventually leads to a point when Na⁺ depolarizing current is much higher than K⁺ repolarizing current; this point is called **THRESHOLD POTENTIAL**. From the moment it is reached, the process can not be reverted again and there is an abrupt inversion of membrane polarity, that is, the action potential. In the majority of neurons, the value of threshold potential is around -30mV.

Once the threshold is attained, the action potential occurs with a fixed amplitude and duration. If the threshold is not attained, that is, if the depolarization of the sodium intake was not strong enough, there is no action potential. That is why the scientist called this an "all or none" phenomenon, much alike a digital mechanism (0 or 1)

Back to Normal

The depolarization phase of action potential is abrupt and very rapid: it takes place in less than one millisecond. Soon after reaching the maximum peak of depolarization (which inverts the membrane potential to some +10 to +20 mV), it begins to return to normal, that is, towards its value at rest. This phenomenon is called **repolarization**, and something very important takes place: while this recovery is going on, the neuron remains insensitive to new stimuli (the **refractory period**).

Why does it happen? To understand it, we have to know another important difference between Na⁺ and K⁺ channels: the first undergoes inactivation but not the latter.

After the action potential occurs, the Na⁺ channels change to an inactive state during which they are unable to respond to a new stimulus, that is, they remain closed to new intakes of sodium. Meanwhile, the K⁺ channels, that are still opening themselves, due to its characteristic slowness, remain open and allow an import out flow of K⁺ ions. This leads to the repolarization of the membrane, that we mentioned above. It can "undershoot" in its final phase, provoking a small and transient **hyperpolarization**.

Sodium channels can only be stimulated again after the membranes are completely repolarized. If there is no sufficient number of Na⁺ channels in this situation, it is possible to stimulate the neuron, but it will respond only if the intensity is much higher. This constitutes the so-called **relative refractory period**. When the channels are completely closed and it is impossible to stimulate the neuron, no matter how intense may be the stimulus, we call it the absolute refractory period.

See also: ["How Nerve Cells Work. Part I"](#)

See in the next installment of the series: The propagation of action potential throughout the nerve fiber (myelinated and unmyelinated fiber, continuous and saltatory conduction. Composite action potential (fibers). The speed of action potential and how it can be measured. Clinical relevance.

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