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Electrophysiology and Nerve Stimulators

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1) Summary of Electrophysiology

The flow of electrical charge from one point to another is called current. The amount of charge that moves between two points depends on two factors: the voltage and the resistance (impedance). The relationship between voltage, current and resistance is given by Ohm's Law:

$$\text{Current (I)} = \frac{\text{Voltage (V)}}{\text{Resistance (R)}}$$

The **resting membrane potential (RMP)** refers to the potential difference between the inside of the neuron and its surface in an unexcited state. The average RMP measured in a neuron is approximately -70mV . The minus indicates that the inside of a neuron's membrane is negatively charged with respect to the outside. It is thus **polarized**.

The RMP is generated by differences in the ionic composition of the intracellular and extracellular fluids. The cell cytoplasm contains a lower concentration of sodium (Na^+) and a higher concentration of potassium (K^+) than the extracellular fluid surrounding it.

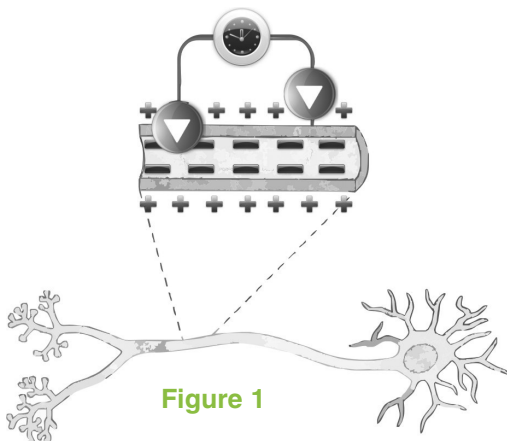


Figure 1

Potential difference as measured over the cell membrane

Depolarization is a reduction in membrane potential: the inside of the membrane becomes less negative than the resting potential. For instance, a change from a resting potential of -70mV to a potential of -50mV is a depolarization.

Hyperpolarization occurs when the membrane potential or voltage increases, becoming more negative than the resting potential. For example, a change from -70mV to -90mV is hyperpolarized.

Depolarization increases the probability of producing an action potential, whereas hyperpolarization decreases this probability.

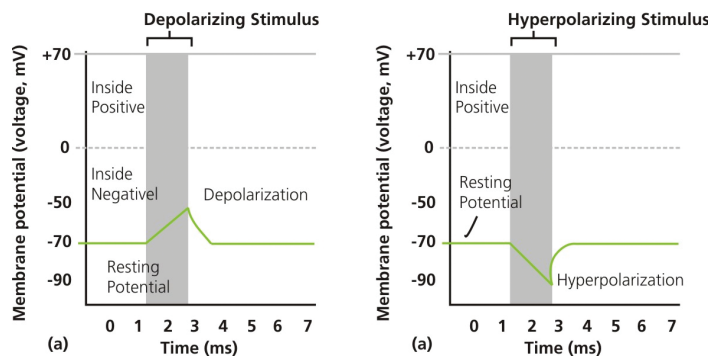


Figure 2

2) Action Potentials

Neurons are highly responsive to stimuli. When a neuron is adequately stimulated, an electrical (ionic) impulse is conducted along the length of its axon. This electrical phenomenon, called the **action potential** underlies virtually all functional activities of the nervous system.

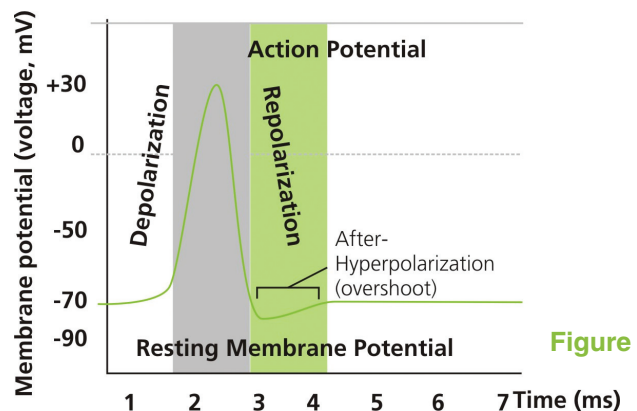


Figure 3

The principal way in which neurons communicate is by generating and propagating action potentials (APs), and only

cells with excitable membranes (neurons and muscle cells) can generate action potentials. An action potential is a brief reversal of membrane potential with a total amplitude (change in voltage) of about 100 mV. The whole event is over in a few milliseconds. A neuron only transmits an action potential when it is adequately stimulated.

The outside of a 'resting' nerve is charged positively. If one adds negative electrons to the outside of such a nerve, its charge will be neutralized. This will, in turn, cause the nerve to depolarize, which will then create an action potential. This action potential will wash down the nerve towards the synapse. A nerve stimulator supplies electrons to depolarize a nerve.

A threshold stimulus must be applied to a nerve in order to trigger an action potential. This threshold stimulus is determined by the **total charge** delivered to the neuron. In the case of an applied square wave this charge is equal to the product of the applied current strength (measured in milliampere [mA]) and the duration of the pulse or pulse width (measured in milli second [ms]):

$$Q \text{ (measured in micro Coulomb)} = I \text{ (measured in mA)} \times t \text{ (measured in ms)}$$

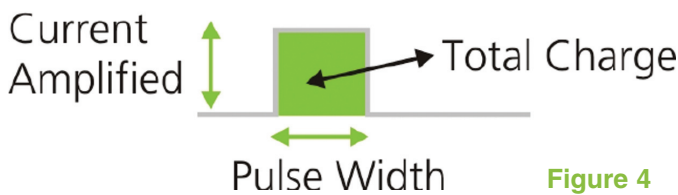


Figure 4

3) Cathode vs. Anode

As discussed in 1.2 the outside of a 'resting' nerve is charged positively. If negative electrons are added to the outside they will neutralize the charge. This will cause the nerve to depolarize, which will then create an action potential. Thus, if the cathode (negative electrode) of the stimulator is placed proximal to the target nerve it will effectively depolarize the nerve.

If the anode (positive electrode) is placed proximal to the target nerve, the current causes hyperpolarization adjacent to the anode and a ring of depolarization distal to the electrode. This arrangement is less efficient in propagating the stimulus and has clinical implication.

4) Constant Current vs. Constant Voltage

When connecting a nerve stimulator to the patient, one has to consider that different peoples' skin impedances as well as the connection between the electrodes and the skin are not constant. For example, If the electrodes dry out, or are even slightly detached from the skin their resistance will increase.

There are two ways a nerve stimulator can respond to this change i.e. with a constant voltage or a constant current. Ohm's Law gives us the equation: **Voltage (V) = Current (I) X Resistance (R)**

Constant Voltage Nerve Stimulators

Constant voltage nerve stimulators are relatively easy and cheap to make. Unfortunately, if the voltage remains constant when resistance increases then the current must decrease. As a result the nerve may not be completely stimulated. This will give the anaesthetist a false indication of the proximity of the nerve.

Constant Current Nerve Stimulators

Constant current nerve stimulators are the safest but also the most expensive to build. As the resistance of the electrodes goes up they compensate by increasing their voltage. As a result the current stays constant, and the stimulation of the nerve remains constant. Any change in response occurs at the neuromuscular junction or in the muscle itself.

5) Pulse widths and chronaxie thresholds

Rheobase is the threshold current for an infinitely long-duration stimulus. Chronaxie, the excitability constant, is the duration of a pulse of current of twice rheobasic strength.

It should be noted that, although there are many published values for chronaxie for various excitable tissues, the range of variability for a given tissue type is quite large. It is generally assumed, however, that nerves can be classified according to their chronaxie thresholds as follows:

The result of the study presented in **Figure 5** clearly shows that chronaxie presents a reasonable guideline for the most charge efficient stimulating pulse width. From the above table it would seem reasonable that the ideal pulse width to

Classification	Chronaxie	Diameter (microns)	Sensory functions
A(alpha)	40-100 ms	10 - 20 (myelinated)	Predominantly motor neurons. These nerves also have the following sensory functions: Proprioception, hair receptors, vibratory sensors, high discrimination touch
A(delta)	150 ms	<5 (myelinated)	Deep pressure and touch, pricking pain, cold
C	400 ms	0.5 - 2 (unmyelinated)	Crude touch and pressure, tickle, aching pain, cold, warmth

Table 1

facilitate a motor nerve response in A -alpha would be around 100us. If the pulse width is increased beyond chronaxie to 1ms there would be only a slight decrease in the current amplitude required to facilitate an action potential. Thus the required current amplitude will decrease non-linearly with the increased pulse width. The net charge needed to facilitate a response at 100us would be less than the net charge needed to facilitate a response at 1ms.

Another consideration should be that, at higher pulse widths the charge densities on the electrodes will increase and could potentially become harmful.

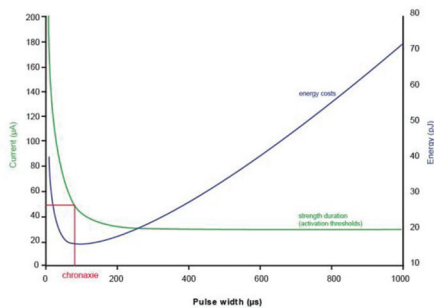


Figure 5

6) Impedance

The impedance of a circuit element is defined as the ratio of the phasor voltage across the element to the phasor current through the element:

$$Z_R = \frac{V_r}{I_r}$$

In other words, impedance is the frequency dependant resistance as presented by its real and imaginary components. In the human body different tissues have different impedance spectra and can be modeled by an equivalent circuit comprising resistive, capacitive and inductive components.

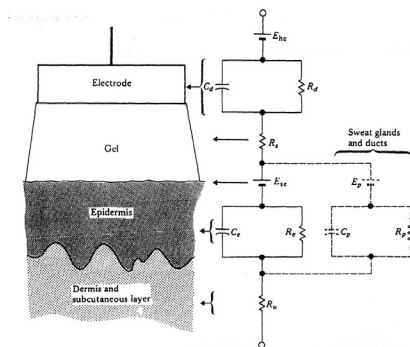


Figure 6

When considering different effects of electrical stimulation, equivalent models of electrode and tissue impedance can help to explain certain stimulation phenomena which may seem inconsistent to the clinician.

Figure 6 shows an equivalent model, demonstrating the different impedances to be considered when analyzing the electrode, gel, epidermis, and dermis.

It should become clear that the total impedance path through which the electric field, generated between two electrodes, propagates is the complex result of the summation of the unique impedance spectra of various types of tissue. Each different stimulating pulse width, as well as its rise and fall times present different frequency components which will result in different unique impedances.

7) Current Selected as opposed to Current Delivered

When one stimulates the nerve with a good current source, the shape and amplitude of the stimulus pulse will always be as selected, as long as the stimulator can deliver the voltage required to accommodate for the varying circuit impedances. All brands of stimulators are limited in the way that they can accommodate varying impedances, by their maximum voltage.

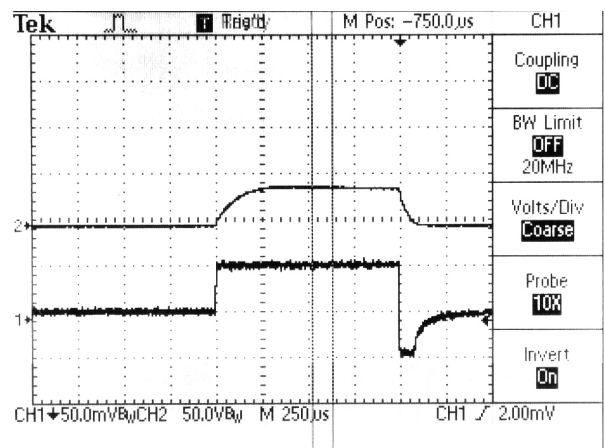


Figure 7

Figure 7 shows a typical current and voltage stimulation response. Voltage (V) indicated as channel 2 is measured across the two electrodes connected to a subject's body. Current (I) indicated as channel 1, is measured over a 10ohm resistor connected in series with one of the electrodes. The maximum current as displayed in this picture is 5mA. The maximum voltage necessary to facilitate this is approximately 40V. Even though stimulation was done with a 5mA, 1ms square wave stimulus, the approximately 80ms negative current component is indicative of the reactive impedance of the combined electrode, tissue impedance.

Figure 8 shows the stimulator at the same settings however the impedance of the electrode/ epidermis interface was increased to a level where the device could not supply enough voltage to facilitate the increased impedance.

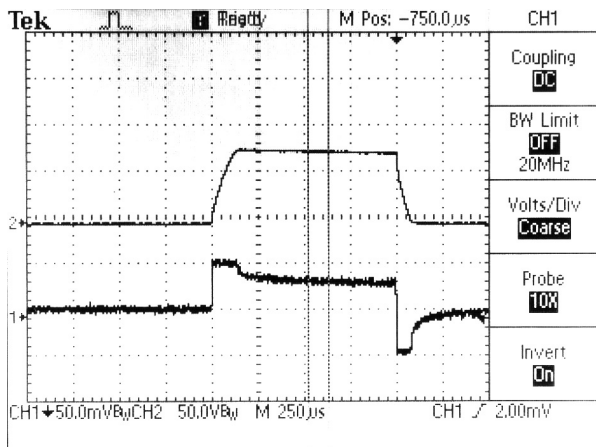


Figure 8

It is clear that after approximately 140µs the device could not deliver the required voltage. The current immediately dropped to around 4mA. One approach to offer the user an indication of the net stimulus effect would be to average out the total current delivered. This would give the user the impression that the observed response was equivalent to a perfect square wave of 1ms pulse width and 3.7mA amplitude. However, as seen in the discussion in the paragraph 1, it should be noted that most of the neuromuscular stimulating response was most likely facilitated in the first 100µs of the stimulus at 5mA. **The average stimulating amplitude could therefore be a misleading representation of the entire procedure.**

In other words it could be argued that the stimulation as indicated in Figure 3 and the one in Figure 4 could elicit exactly the same neuromuscular response (contraction) with the electrodes positioned at exactly the same distance from the target nerve. If one simply relied on the information presented of an actual average current transferred, one would have the erroneous impression that the cathode in eliciting a response such as in the case of **figure 8** would be closer to the nerve than the cathode that elicited the same response in the case of **figure 7**.

6.10) Sources

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