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Lab H1
April 27, 2012

The Physics of Electricity in the Body

The United States and most of the modern World is obsessed with cool gadgets from companies like Apple, Samsung, and Toshiba. What goes unknown as a student types an email on her iPad is the amount of electricity going through her body in order to perform that task.

The aim of this paper is to view electricity in the body from several viewpoints. The interesting processes that take place in the nervous system will be discussed. Several common medical tests including the EMG, EKG, and EEG will be explained. Several uncommon medical tests including the ERG, EOG, MCG, and MEG will be mentioned as well. Finally, some additional applications of electricity in the body will be discussed including bone growth and controlled biofeedback.

To begin, the nervous system is a highly electrical system. Its main purpose is physiological communication in the body from electrical signals (McCall 2010). For a roadmap, the overall process, including the different parts of the nervous system, the role of nerve fibers, and the structure of a neuron will be explained. Later, the mechanism by which it works will be discussed. Last, the overall structure and significance will be reviewed.

McCall (2010) explains the overall nervous system function and its sectors. The nervous system is setup to respond to stimuli from the environment, such as someone shocking you after rubbing their socks on the carpet, and stimuli from internal organs, such as the brain. These stimuli are sensed, processed, and responded to all according the nervous system. The sensing and the response are carried out by the peripheral nervous system. The processing is carried out by the central nervous system, including the brain and spinal cord.

In both the peripheral and central systems, McCall (2012) explains how nerve fibers are involved that respond to the initial stimulus in the form of an electrical signal. Nerve tissue can be organized into neurons that communicate electrical signals in response to stimuli and neuroglia that provide structural support for the neurons. A stimulus will first be sensed, or detected, by a sensory nerve receptor which will transport the electrical signal to the sensory neurons. These neurons will pass the signal to the interneurons in the central nervous system which will process a response to the stimuli. Next, the signal will be transferred to motor neurons which transport the signal to the organ the signal was destined for. That organ will then carry out its role. A good example of this is a signal initiating heart contraction.

McCall (2010), Gustafson (1980), and Cameron, Skofronick, and Grant (1999) explain the structure of an individual neuron. Each contains a small spherical portion that is the cell body (Figure 1). The cell body is surrounded by dendrites, which are the tendrils that detect electrical signals from other neurons. The axon is a large tendril jutting out like a string or “tail” from the neuron. The electrical signal will be detected by the dendrites which will transfer the electrical signal to the cell body. The cell body will transfer the signal to the axon which contains nerve endings or axon terminals that will transfer the signal to another neuron or organ. The axons of

neurons will line up such that neurons act in bundles. The axon may contain a fatty insulating layer of neuroglia called myelin.

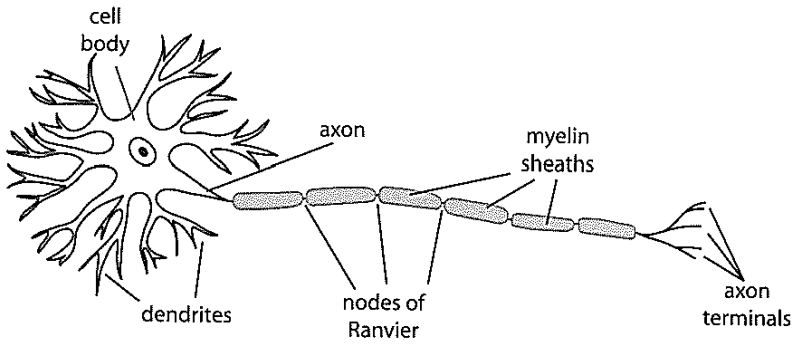

Figure 1. Structure of a neuron (McCall 2010, p. 161)

The detailed mechanism by which an electrical signal travels through a neuron is explained by McCall (2010). First, the normal equilibrium – no signal transfer– state of the neuron will be explained. Second, action potentials will be discussed. Third, the overall structure will be revisited and integrated.

An axon contains a membrane that is permeable to some ions and less permeable to others. It is more permeable to potassium ions that it is sodium ions. Initially, a significant concentration of potassium ions exists within the axon portion of the cell and a significant portion of sodium ion exists outside of the axon portion of the cell. Because of diffusion and permeability, more potassium ions will exit the axon that sodium ions enter. Thus, the interior will have an overall negative charge and the exterior a positive charge. Thus, a membrane potential difference exists such that a resting potential difference of around -70 millivolts is the equilibrium value. This negative value is established from a reference point outside of the axon such that a lower electric potential difference value exists within the axon and a higher electric

potential difference value exists outside of the axon. A variance of around 20-30 millivolts will exist for resting potential difference values of different cell types.

When a signal is detected by the dendrites of a neuron that causes a 15-20 millivolts or higher increase in the resting potential difference, an action potential will be summoned. During an action potential, a depolarization process occurs such that the membrane increases its number of channels that allow for the diffusion of sodium ions. There is thus an increase in the sodium ions within the axon and the interior becomes increasingly positively charged. This uptake of sodium ions will increase the potential difference up to around positive thirty millivolts and then the channels will begin to close. This initiates the repolarization process. Additional potassium ions – the ones that did not diffuse initially –will rush out of the axon decreasing the potential difference back to the resting potential value. The resting potential difference will be restored, but the ions will be on the wrong sides, so a sodium/potassium pump will actively transport (using ATP) the ions to their equilibrium locations. The initial 15-20 millivolts or higher is the threshold potential; after that change, an action potential will be initiated.

McCall (2010) and Gustafson (1980) explain how the overall structure can be integrated after understanding the mechanism. These action potentials initiate the action potentials of nearby axons starting a chain reaction or domino effect. After a stimulus, the action potential travels from the sensory neurons to the interneurons finally to the motor neurons. This process is a positive feedback mechanism such that each action potential causes the movement of ions within an adjacent axon.

Gustafson (1980) explains how significant these action potentials are for axons. The diameter of an axon is around eight nanometers thick. During an action potential, the change in

potential difference is around 100 microvolts. Dividing this change by the diameter of the axon, a huge 1.25 million volts per meter is calculated. Since the action potential movement can last in the range of nanoseconds (Cameron, Skofonick, and Grant 1999), axons handle significant amount of charge in a short time period.

These action potentials that are critical in physiological communication play a role in several medical tests. The common EMG, EKG, and EEG will be discussed along with the less common ERG, EOG, MCG, and MEG. To start, the general components of an EMG and electrical stimulation EMG will be discussed.

Cameron, Skofronick, and Grant (1999) describe the electromyogram (EMG). An EMG records the electrical signals – seen as action potentials – that cause muscles to contract. These are motor neurons. Measurements can be taken in such a way that a concentric needle electrode is inserted under the skin and an individual neuron is measured for its action potential. Measurements of bundles of neurons can also be taken where electrodes are pressed to the skin and a subject will contract his muscles. This activity can be seen on an oscilloscope that shows volts and (volts)(seconds).

Cameron, Skofronick, and Grant (1999) also explain the advantage of electrical stimulation EMG and several variables that can be measured. Because the action potentials during a voluntary movement can be erratic, electrical stimulation has the advantage of getting more standard data. Some variables that can be measured include the latency time, or the time between the stimulation and a response, and the magnitude of the action potential. The results can be contrasted with normal individuals or symmetrical muscle groups to determine any abnormalities. Another unique variable to measure is the conduction velocity. After a stimulus,

electrodes of measured distances can see the velocity of the signal as it travels. A normal individual would show a conduction velocity from 40-60 m/s while an abnormal individual might show a 10 m/s conduction velocity. After multiple stimulations an EMG of an individual with myasthenia gravis will show no response whereas a normal individual should continue to show response as long as there is a .2 second relaxation time.

The electrocardiogram, or ECG/EKG, is similar in many ways to the EMG. McCall (2010) describes how the beating of the heart causes action potentials to move through the neurons that connect to the heart. This is the result of an electric field. An electric potential difference can be measured if electrodes are attached to various points on the skin. The EKG records these potential differences.

The mechanism for this process is explained by Cameron, Skofronick, and Grant (1999). The neurons that connect to the heart will cause the sinoatrial node within the right atrium of the heart to contract. This causes an electrical pulse. This pulse will trigger the contraction of the atrioventricular node. Each node contraction is accompanied by the pumping of blood within the top chambers – atria – and the bottom chambers – ventricles. In general, the atria pump blood to the ventricles which pump blood to the lungs to be oxygenated and into general circulation. This blood eventually returns to the atria and the cycle starts over. This process can be categorized by atrial and ventricular depolar- and repolarization (Figure 2). These can be seen on an oscilloscope as waves. The atrial depolarization and ventricular repolarization are accompanied by relatively small potentials, as shown as P and T waves, while ventricular depolarization is accompanied by a large potential difference shown as a QRS wave (Figure 3).

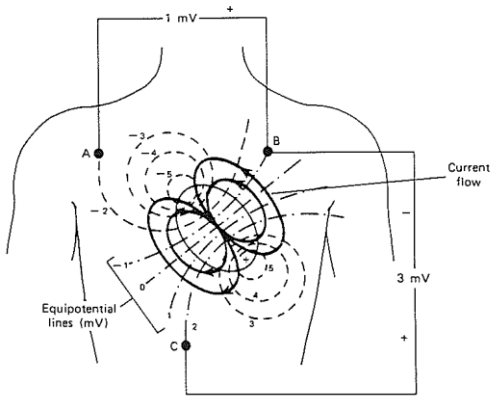

Figure 2. Potential distribution of half-depolarized ventricles (Cameron, Skofronick, and Grant 1999, p. 235)

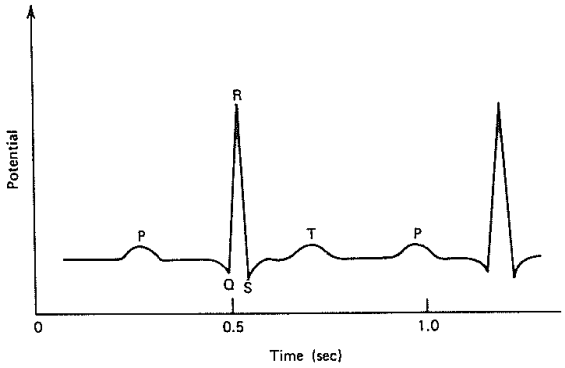

Figure 3. Typical EKG waves. (Cameron, Skofronick, and Grant 1999, p. 239)

In practice, an EKG has many applications (Cameron, Skofronick, and Grant 1999). Cardiologists are experienced in detecting problematic or abnormal rhythms of the heart. Computers can assist in this process as well. An EKG is an integral part of the regulation of surgery. For individuals with rhythm problems, a pacemaker can be inserted into the body that acts to correct abnormal rhythms with electrical pulse (Gustafson, 1980).

The electrical signals within the brain can be measured with an electroencephalogram, or EEG, as discussed in Cameron, Skofronick, and Grant (1999). After attaching several electrodes to the scalp, electrical signals can be measured that indicate mental activity and brain health. For example, a non-focused state is characteristic of alpha waves of 8-13 Hz. A focused mental state is characterized by beta waves of greater than 13 Hz. Regarding brain health, if the signals from one side of the brain are different in magnitude from the signals from the other side, this could be an indication of disease. Similarly, if an area has uncharacteristically low electrical activity, this could be a sign of a tumor. For individuals with epilepsy, attacks show huge jumps in electrical potential difference values in an EEG.

Cameron, Skofronick, and Grant (1999) explain some lesser known tests of electrical activity including two involving the eyes and two that are the result of moving charge.

Two tests involving the electric activities of the eyes include the electroretinogram (ERG) and the electrooculogram (EOG). ERGs are carried out by attaching an electrode to a lens and placing this lens on the eye. Stimulation is provided by a “flash of light” and the electrical potential difference values are measured. In an individual with retinitis pigmentosa, the B wave seen in normal individuals will not be measured. The electrical potential differences associated with mechanical movement of the eyes is measured by an EOG. While straight forward is assigned a value of zero (Figure 4), changes in the position of the eyes cause electrical signals that can be monitored for drug testing and sleep research.

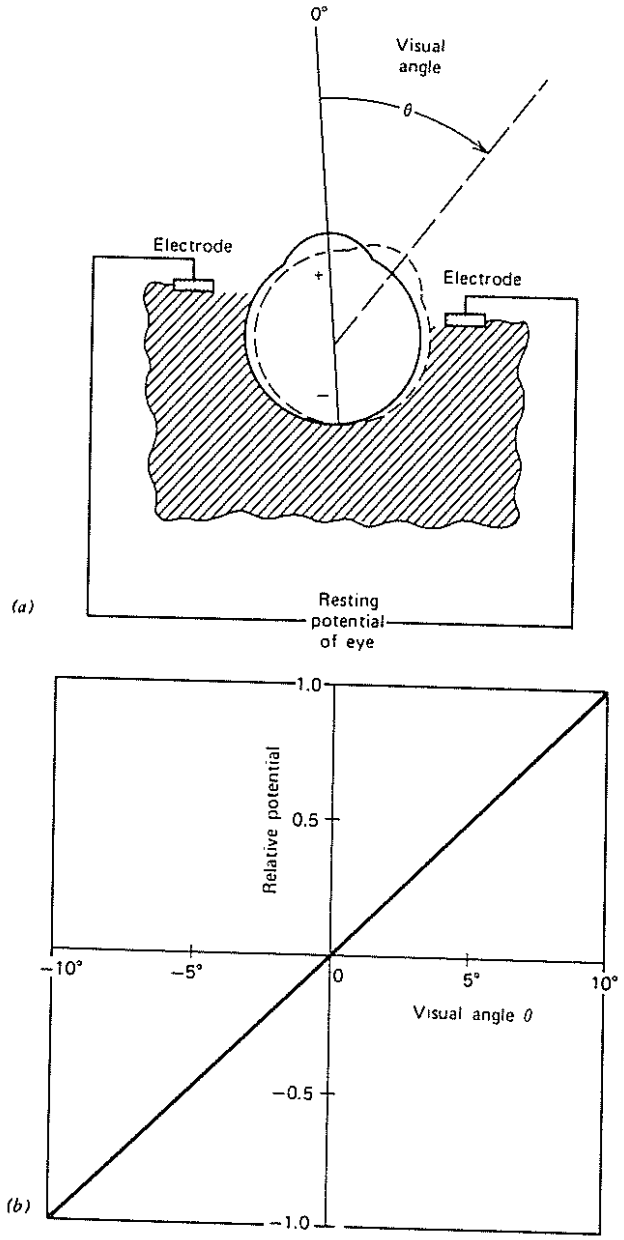

Figure 4. Components of EOG. (Cameron, Skofronick, and Grant 1999, p. 250)

Movement of charge results in a magnetic field. Thus magnetic fields exist throughout the body. Those fields can be tested in the heart with a magnetocardiogram, or MCG. Those fields can also be tested in the brain with a magnetoencephalogram, or MEG. The heart has a

magnetic field of around 50 picoTesla while the brain has a magnetic field of around .1 picoTesla. Since these fields are so small, the measurement process is sensitive. Devices like the Superconducting Quantum Interference Device, or SQUID, that can detect fields as small as 10^{-14} Tesla are used. While the practicality of the MCG is still in question, the MEG can be used in finding the location of electrical signals – a flaw of the EEG.

Various applications of electrical activity in the body are discussed in Cameron, Skofronick, and Grant (1999), including bone growth and controlled biofeedback.

Bones are piezoelectric in that a stress or pressure applied will induce a flow of charge. Collagen which acquires a negative charge during to piezoelectricity and apatite which acquires a positive charge act as semiconductors producing a current in bones. This current promotes bone growth. When bones are broken, this current is an "injury current." It has been found that small amount of external current – around 1 to 3 nA – can actually improve fractured areas.

Another interesting application is the idea of controlled biofeedback. Biofeedback is generally automatic and uncontrolled reactions such as sweating or the adjustment process of an individual's eyes to sunlight. It is possible that a person can become familiar with the feelings associated with certain brain waves by monitoring his or her EEG. Thus, if certain brain waves are associated with a headache, a person can recognize those brain waves and concentrate in order to avoid the initiation of those waves. In this way, the idea of controlled biofeedback is possible.

In conclusion, this research paper discussed the nervous system, several common and uncommon electrical signal tests, and some general applications of electricity in the body. One of the most interesting things about this research is the fact that so much is unknown, including for

example the complexities of brain waves (Cameron, Skofronick, and Grant 1999). With the rapid technological advances of the first decade of the twenty-first century, it will be interesting to see where the research goes.

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