Measuring the Action Potential in a Nerve Using a Toroid

An Honors Thesis (HONR 499)

By

James Kyley Underwood

Thesis Advisor
Dr. Ranjith Wijesinghe

Ball State University
Muncie, Indiana

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Abstract

For years the only way to test for nerve damage was to place two electrodes on the nerve and test the voltage between them. While this method can be used to test for nerve damage, it can be quite painful. It will also not give a high amount of detail without being performed multiple times, causing more pain to the patient. The experiment I have been a part of will test a possible solution to this problem. Through the use of a toroid the nerve can be tested with considerably less pain and to a greater degree of accuracy. While this experiment has been in progress for almost a decade, I have only been a part of it for the last year. My research group is in the process of collecting data in the near future. I will explain the fundamental physics behind the experiment, the devices used to imitate the conditions in which the experiment will be performed, and what we expect to learn from the experiment.
Acknowledgements

I would like to thank Dr. Ranjith Wijesinghe for both allowing me to take part in this research project and also pushing me to continue to further my education in the career of medical physics.

I would like to thank Camrin Tipton, Zak Summitt, and Will Jay for their work in this project. Specifically, I would like to thank Camrin Tipton for suggesting me for this research project and also spending the time to explain the inner workings of the equipment in the beginning of my involvement.
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Chapter 1:

Introduction and Purpose

The purpose of this thesis is to explain the experiment that we have been preparing in a manner that is both comprehensive and understandable to the general public. While it does require a certain understanding of human anatomy and physical principles, the necessary background in both subjects will be provided in Chapter 2 and Chapter 3, respectively. Chapter 2 introduces the concept of “Action Potential” through which the human body sends signals containing information to the brain. Chapter 3 introduces the toroidal Inductor, or “toroid”, and explains how it can be used to measure voltage within an object without making direct contact with the object. Chapter 4 bridges the gap between physics and human anatomy by explaining how the Toroid can be used to measure the Action Potential in a nerve. Chapter 5 introduces the equipment used to replicate a human nerve which allows the experiment to be tested. Chapter 6 introduces the program used to save and analyze data collected during the experiment, which is also modified to remove statistical errors in the equipment. Finally, Chapter 7 discusses the expected results from the experiment and their implications.

My role in the experiment was quite small in the grand scheme of things. Prior to my involvement, our research group had spent a great deal of time on setting up the equipment and troubleshooting the LabView program and DAQ Assistant. While another colleague of mine, Will Jay, was working on his own research project of using an MRI to detect neural signals, he did play a large role in the experiment we are performing.

During my involvement in the experiment, I was responsible for assisting my colleagues, Camrin Tipton and Zak Summitt, in creating the correct calibration pulse and secondary pulse from the two pulse generators. After we accomplished this, we turned our efforts to constructing a working program for data acquisition and signal averaging. I was able to apply my knowledge of the LabView program, and also contributed to the data acquisition method. I learned how to troubleshoot the scientific equipment and manipulate the pulse generator and compensator in order to create the waveform necessary.

In addition to the technical knowledge gained from this project, I learned a great deal about how the human body transmits signals which was then reinforced in a medical physics class taught by Dr. Wijesinghe, also our research advisor. In the past two years, I have learned more about how the human body interacts with its surroundings than I had in any of my biology and physics classes prior. Participating in this experiment solidified my learning experiences.

This research project and thesis have allowed me to apply a great deal of the skills and information I learned in higher level physics courses to a real life project, which only helped to reinforce that knowledge. I see this research project and thesis as one single entity and their combined role in my education has helped shift my future career choice to that of medical physics.
Chapter 2:

An Overview of Nerves and Action Potential

The human body is effectively a giant computer. Information is collected by small sensors and transmitted to a central processor to be analyzed. Two main types of nerves exist in the human body. The first type is the motor (anterior) nerve, which transmits signals from the brain to the various muscles in the body. These nerves are responsible for telling the muscles when to move. The second type is the sensory (posterior) nerve. These nerves act as the sensors in the body and transmit signals about the tissue and outside environment to the brain. The sensory nerves are responsible for every feeling or sense that a human experiences [5]. A typical nerve cell is shown in figure 2.1.

Figure 2.1: A typical nerve cell.
(Image obtained from http://hyperphysics.phy-astr.gsu.edu/hbase/biology/nervecell.html)

The axon is the part of the nerve cell that transmits signals from one cell to another. The dendrites are then responsible for receiving those signals and transmitting them to the axon of another nerve. The axon in a nerve can be up to 1 meter long and is approximately 0.1 to 20 μm in diameter. [6] The transmission speed of the signal varies depending on the physical characteristics of the axon.

The type of nerve cell, meaning the type of message they transmit, determines the physical characteristics of the axon. The main difference between the nerves that transmit signals quickly, up to 100 meters per second, and slowly, as low as 1 meter per second, is the myelin sheath surrounding the axon. [6] The myelin sheath is approximately 1 mm long and made up of fatty cells that act as insulators, preventing electrical signals to be transmitted through them. While this seems like it would slow down, or prevent, electrical signals being transmitted, it actually accelerates the process. The signal is accelerated because not all of the axon is coated in the myelin. Small sections of the axon are left uncoated and are called Nodes of Ranvier. These nodes allow the signal to be transmitted, but instead of the signal effectively pushing itself down the nerve, the myelin forces it to jump from node to node, a much faster transmission process.
Signals are transmitted electrically through the nerve. This electrical signal is created by a concept called “Electrochemical Potential”. The voltage that exists between the nerve and its surrounding is created by the ion distribution. The ions in a nerve, shown in Figure 2.3, consist mostly of sodium, a positive ion, potassium, a positive ion, and chloride, a negative ion, among other miscellaneous positive and negative ions. These ions have different concentrations inside and outside of the nerve and are held slightly out of balance. The axon typically contains a large number of potassium ions, whereas the sodium and chloride are held in a much lower concentration inside the axon than outside. These concentration differences create the potential difference that occurs between the nerve axon and the fluid around it. When the nerve sends a signal, the concentrations of these ions change, thus changing the voltage. [2]

Action Potential, shown in Figure 2.4, is measured to be approximately +40 mV, or +0.04 volts. While this may not seem very high, the resting voltage, or voltage in the nerve when no signal is being transmitted, is approximately -70 mV. When a signal is transmitted, it resembles a pulse. It rises quickly from -70 mV to +40 volts, and then drops to -90 mV before slowly rising back to -70 mV. This process is considered to be the depolarizing and then re-polarizing of the nerve. Through this method, signals are sent throughout the body. [2]
Figure 2.3: The concentration of ions within and outside the nerve axon. [Hobbie & Roth, 137]

Figure 2.4: The Action Potential in a nerve axon. [Hobbie & Roth, 136]
Chapter 3:

The Physics of a Toroidal Inductor

A toroid is chosen for this experiment for several reasons, the shape being the most obvious. This shape lends itself very well to measuring the action potential of a nerve. However, the more useful and less intuitive reason comes from the geometry of the toroid. A toroid consists of a metal ring wrapped tightly in a long wire. The wires wrapped around the toroid create individual amperian loops. Amperian loops correspond to a concept presented in electrodynamics which describes how a magnetic field is created by a closed loop of current. Ampere's law in integral form, shown in Eq. 3.1, can be used to calculate the magnetic field vector for any closed loop of current.

\[ \oint B \cdot dl = \mu_0 I_{enc} \]  
(Eq. 3.1)

Where \( B \) is the magnetic field, \( dl \) is the differential path element, \( \mu_0 \) is the permeability of free space, and \( I_{enc} \) is the current enclosed in the loop. [Giffiths, 225]

Due to the circular symmetry of the wire loops and the fact that the resulting magnetic field is constant, the left side of Eq 3.1 becomes simply \( B(2\pi s) \), where \( s \) is the radius of the circle. Solving for \( B \) gives a magnetic field of \( \frac{\mu_0 I_{enc}}{2\pi s} \). However the direction of the field depends on the direction of the current flow. Within Ampere's Law, there is a hidden cross product that does not directly appear in Eq. 3.1. Therefore, the direction of the magnetic field is always perpendicular to the flow of current. [1]

This concept is applied many times in a toroid. With each loop of the wire acting as an amperian loop, the entire magnetic field created by this loop is contained within the metal ring. The fact that the magnetic field is contained entirely within the circular loop is what allows the toroid to be used in the experiment.

In order to understand how a wire is able to induce a magnetic field on the toroid, the concept of flux must be used. Flux is the amount of physical quantity travelling through a specific area. Specifically, in the case of the experiment, the magnetic flux is the amount of the magnetic field that is travelling through a specific area. The general equation for magnetic flux is presented in Eq. 3.2.

\[ \Phi_M = \int B \cdot da \]  
(Eq. 3.2)

Where \( \Phi_M \) represents flux, \( B \) represents the magnetic field, \( da \) is the differential area element [Griffiths, 295]

To find the magnetic flux generated by a nerve, the model for a current carrying wire can be used. From Eq. 3.1, it has been found that the magnetic field from a wire is equal to \( \frac{\mu_0 I_{enc}}{2\pi s} \). However, because of the constantly changing direction of the wire; the direction of this magnetic field became more of a challenge to understand. Figure 3.1 depicts the direction of the magnetic field created by a current carrying wire when the current is travelling out the page.
The orientation of the magnetic field created by a current carrying wire lends itself perfectly to the use of a toroid. When the toroid is placed around the wire, the magnetic field lines up with the magnetic field that would be created if the toroid had current flowing through it. However, this coincidence does not finish the explanation of how a voltage is induced in the toroid. In order to complete this explanation, one more equation must be introduced.

The final piece of the puzzle lies in Faraday’s Law of Induction and Lenz Law. Faraday’s Law of Induction states, “Whenever (and for whatever reason) the magnetic flux through a loop changes, an emf will appear in the loop.” [Griffiths, 302] This simply means that if the magnetic flux changes, a voltage is induced. Lenz law simply states, “Nature abhors a change in flux” [Griffiths, 302], which is characterized by the negative sign in Eq. 3.3.

\[ \varepsilon = -\frac{d\phi}{dt} \]  

(Eq. 3.3)

Where \( \varepsilon \) represents the induced voltage, \( \phi \) represents the flux going through the loop, \( t \) represents the time, and \( \frac{d\phi}{dt} \) is the time derivative of the changing magnetic flux. [Griffiths, 302]

With these physical concepts, the toroid can detect a change in current in the wire, or nerve, without having to make direct contact.

Figure 3.1: The magnetic field generated by a current carrying wire with the current traveling out of the page. [Griffiths, 221]
Chapter 4:

How to Imitate the Experiment With Lab Equipment

Collecting data with the Toroid requires testing on an actual nerve. For testing purposes, the sciatic nerve can be used as it is the largest nerve in the frog’s body and most closely resembles a human nerve. Unfortunately, once the nerve is removed it will only transmit signals for a limited period of time while it is immersed in a saline bath. This creates a problem when trying to set up a test using the Toroid and data collection program. Due to the limitations of using actual nerves to prepare the experiment, such as the logistics of storing frogs and the humane aspect of sacrificing multiple frogs, real nerves cannot be used. In the place of actual nerves, lab equipment must be used to replicate the signal that an actual nerve would produce. While a nerve and wire are physically very different, their basic function is to transmit a signal from one point to another, therefore a wire will be a sufficient imitation.

The first piece of equipment used to imitate the experiment is a pulse generator and a high and low frequency compensator, shown in Figure 4.1. The function of this piece of equipment is two-fold. First, it creates a calibration pulse, which is set to 50 μA. Secondly, it filters the signal received by the Toroid so that both the high and low frequency signals are removed, leaving only the pulse sent from the Toroid.

The calibration pulse is necessary, as it allows the pulse detected by the Toroid to be interpreted more accurately. The pulse created by the Toroid is determined by many factors, such as the geometry and the number of loops of copper wire in the Toroid. The calibration pulse is sent to the oscilloscope and allows the signal received from the Toroid to be compared to a pulse of known amplitude. In addition to a reference pulse, the calibration pulse also triggers the second pulse generator to send a signal that is received by the stimulus generator.

The second pulse generator, shown in Figure 4.2, simply produces a pulse of varying event interval, delay, width, and amplitude. The event interval was set to 1 second, the delay is set to 10 ms, the pulse width is set to 1 ms, and finally the amplitude is set to +5 Volts. This event begins when the signal from the first pulse generator is received. The only limiting factors with this device are the pulse width and delay cannot exceed the event interval, and that the amplitude cannot overload the stimulus generator. The pulse that this pulse generator produces is then sent directly to the stimulus generator.

The stimulus generator shown in Figure 4.3 receives the signal from the pulse generator, and sends the signal directly to the circuit. While this may not seem necessary, the stimulus generator plays another important role in the experiment. The stimulus generator simulates the constant current that runs through the nerve at rest. The stimulus generator can provide a constant current output ranging from 1 μA to 10 mA, but is set to .25 mA for the experiment.

The stimulus generator is the final step in creating the simulation for the experiment. Once the pulse generators and stimulus generators are set, the circuit can be built. The circuit is the simplest part of the entire set up. It consists of a simple 1,000 Ω resistor between the positive and negative terminal of the circuit, shown in Figure 4.4. In Figure 4.4, the toroids are wrapped around the wires of the resistor. The toroids are connected to a variable amplifier, shown in Figure 4.5, that allows the subtle differences in the individual toroids to be account for, causing them to send identical signals.

Finally, in Figure 4.6, the oscilloscope displays the calibration pulse and filtered signal received from the toroids. While there are two calibration pulses and two signals from the
toroids, both of these have been calibrated to be identical. This is the same signal that is being received by the computer, and is for programming purposes only. Displaying both signals on the oscilloscope would be redundant.

Figure 4.7 shows the full experimental set up, with the direction of the signal propagation being denoted in the wire diagram.

Figure 4.1: The Pulse Generator used to send the calibration pulse and filter the signal received from the Toroid.
(Image taken in the Medical Physics Laboratory at Ball State University.)
Figure 4.2: The Pulse Generator used to send a signal to the stimulus Generator. (Image taken at the Medical Physics Laboratory at Ball State University.)
Figure 4.3: The stimulus generator, sending a constant current of .25 mA to the circuit. (Image taken at the Medical Physics Laboratory at Ball State University.)

4.4: The circuit and toroids surrounding the wires of the circuit. (Image taken at the Medical Physics Laboratory at Ball State University.)
Figure 4.5: The amplifiers connecting the toroids to the signal filter. (Image taken at the Medical Physics Laboratory at Ball State University.)

Figure 4.6: The display of the oscilloscope, showing both the calibration pulse (yellow), and the filtered signal received from the toroid (purple). (Image taken at the Medical Physics Laboratory at Ball State University.)
Figure 4.7: The full experimental set-up.
(Created in CircuitLab.com.)
Chapter 5: The Program Used to Collect Data

The program designed to collect and store the data was created in LabView, a graphics based programming software that takes code and converts it into a more user friendly interface. With this simpler interface, complex programs can be created in a fraction of the time, with little to no knowledge of coding languages.

The program created had to fulfill two requirements. First, in order to successfully test the equipment used to imitate a nerve, it had to successfully store tens of thousands of cycles of data in a way that allowed the user to access it and interpret it easily. Second, it had to be able to account for the statistical variations in the signals created by the pulse generator and leave only the desired square wave.

The program that finally accomplished both of those goals is depicted in Figure 5.1.

Figure 5.1: The program elements used to achieve the data collection and signal averaging. (Image taken in the LabView program in the Medical Physics Laboratory.)
This program satisfies both requirements in a very simple way, despite the seemingly complex circuit. Statistical variation is common in experiments, and is typically lessened by simply taking multiple sets of data and finding the average of all the data sets. This program collects data automatically and at the correct rate for the experiment.

The program uses a shift register, labeled “1” in Figure 5.1, to perform this averaging function. The shift register performs a function a predetermined amount of times, using the output of one cycle as the input of the next. The program contained within the shift register is the program that is repeated each cycle. Inside the program is a device called the “DAQ Assistant”, labeled “3” in Figure 5.1, which stands for Data Acquisition Assistant. This program element is used to bring the data acquired from the external chip into the LabView program to be analyzed. The circuit elements connected to the DAQ Assistant are called “rate”, “number of samples”, and “stop” allow the user to set how many samples are collected, through “number of samples”, and how frequently these samples are collected, through “rate”. (Display and input shown in Figure 5.2) The “stop” input to allow the user to tell the program to stop collecting data. The output of this element is sent two places, first to a “graph” element that displays the data the DAQ Assistant is processing. This graph is only in place to allow the user to see the incoming data so that it can be compared to the averaged data after several cycles of the shift register. The second place the data is sent is to an addition element. This element simply takes two inputs and adds them together. This sum is then used as the output of the shift register and is then used as the input for the next cycle.

However, at this point in the circuit, nothing has been averaged. The information has simply been added to the input. This is when a set of averaging elements is introduced. The averaging elements are labeled “4” in Figure 5.1. Before the signal can be averaged, the number of cycles must be determined. This is done by using another addition circuit element. The addition element simply takes the number of times the shift register has already run, and adds 1 to it. The number is then sent do a display element called “Times averaged” and also a graph element that displays the new data set.

Before any confusing arises, there is a subtle problem with the averaging method. When the number “1” is added to the number of cycles the shift register has already run, the new average is incorrect. The number “1” is added to the number of cycles because the shift register requires a data set to be entered before it will begin its cycles. This is where the second DAQ Assistant, called DAQ Assistant2, becomes necessary, labeled “2” in Figure 5.1. It performs the same function as the first DAQ Assistant in that it collects a certain number of samples at a certain rate from the same external chip the first DAQ Assistant does. However, this DAQ Assistant does not have a “stop” element in its inputs. The DAQ Assistant2 does not require a “stop” element, as it is only run through one cycle and is only used to start the shift register. Once this is added to the circuit, the “1” becomes necessary to maintain the correct average.

Now that the averaging element has been introduced, the program has all necessary elements to eliminate the statistical variation in the signal it receives. All that is left is the data collection. The data collection is the simplest part of the circuit, in that it simply takes the data from both the original signal and the averaged signal and saves them into a simple text document. This fulfilled both requirements, statistical variation reduction and data storage, and with a working data collection tool, the experiment is finally ready to be performed.
Figure 5.2: The display window of the program.

The experimental process created was built in LabView allows the incoming and average signals to be viewed.

(IMAGE TAKEN IN THE LABVIEW PROGRAM IN THE MEDICAL PHYSICS LABORATORY.)
Chapter 6:

The Experiment and Discussion

The toroid in the experiment consists of a ferrite ring of high magnetic permeability to prevent eddy currents, wrapped tightly in a copper wire. The wire used is a very light, 40 gauge, copper wire, shown in Figure 6.1, and is wrapped 100 or more times around the ferrite core. The ends of the wires are attached to cables, and the entire apparatus is sealed in a layer of epoxy to keep the toroid from making direct contact with the nerve. [7]

The toroids will be connected to the pulse generators in the same way they are in the simulation. The calibration pulse will act as the external trigger for the nerve, causing it to transmit a signal. The toroid will detect the transmitted signal in the nerve and send the signal into the compensator, which will filter out the low and high frequencies. Both the calibration pulse and the signal detected by the toroid will be sent to the computer for averaging and storage. The signal can be both sent and stored approximately 7,200 times, or once per second, within the expected lifetime of the nerve.

The nerve, electrodes, and toroids will be submerged in a tank, shown in Figures 6.2 and 6.3, containing saline solution [7] during the duration of the testing.

At this point, the final piece of the experiment necessary is the nerve itself. Until a nerve is obtained, the experiment cannot move forward. Once the experiment has been performed, the data must be analyzed. If the data confirms that the toroid can indeed differentiate between a healthy and damaged nerve, then new possible experiments can be performed. The next step will be to produce a toroid which can be easily opened and closed around a nerve in the human body. While the toroid used in the experiment will work, it will not be practical for diagnostic applications. The toroid currently used would require the nerve to be severed on one end in order for it to be positioned properly, which would render the nerve useless.

The main goal of the experiment is simply to see if, with current technology, a damaged nerve can be diagnosed without making direct contact. If this proves successful, the next step will be to develop equipment designed to make this procedure viable in the real world. If this proves successful, the pain associated with diagnosing nerve damage will be lessened, if not eliminated.
Figure 6.1: A fully assembled toroid with the epoxy coating. (Image taken at the Medical Physics Laboratory at Ball State University.)

Figure 6.2: Side view of the tank holding the nerve, electrode, and toroids during the experiment. (Image taken at the Medical Physics Laboratory at Ball State University.)
Figure 6.3: Top view of the tank holding the nerve, electrode, and toroids during the experiment. (Image taken at the Medical Physics Laboratory at Ball State University.)
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