

Instrumentation – Amplifiers, Filters, Stimulators and all that Other Stuff we Love to Hate

Learning Objectives:

Most of the industry related materials we read are exciting and fun to read. They are all about diseases and injuries we work with every day. There are those other less desirable topics we are required to know and understand, but are not much fun at all. This paper tackles some of those items, from basic electronics to filters and stimulators. It is our desire to make this easy to read and understand and maybe even a little fun.

We will review:

1. Basic electronic circuits including Ohms's law and properties of alternating current
2. Electrodes and electrode types
3. Amplifiers
4. Filters
5. Analog to Digital conversion
6. Averaging and Signal to Noise Ratio
7. Displays
8. Stimulators and stimulator properties
9. Interference, and
10. Electrical safety

This outline closely follows the contents of Chapter 3 of Dumitru's book (one of our favorites), although the content is found in many sources.

Basic Electronic Circuits:

As an early grade school student we practiced rubbing a latex balloon in our hair and allowing it to stick there, then rubbing two latex balloons in our hair and observing when they would not stick to one another. Little did we know we were learning the basic electrical rule called Coulomb's law, which states "Like charges repel and unlike charges attract." Later the basic electrical charge was named in his honor, the Coulomb.

A circuit is an interconnection of components so that current flows in one or more closed loops. Kirchoff's Law states that the sum of all currents into a node equals the sum of all currents leaving a node.

With respect to DC Ohm's Law, the formula is $(E) \text{ Voltage} = (I) \text{ Current} \times (R) \text{ Resistance}$. A component that has a node in common and does not connect anywhere else is a resistor in series. The resistor in series has the same current, derivative of current and the same voltage in relation

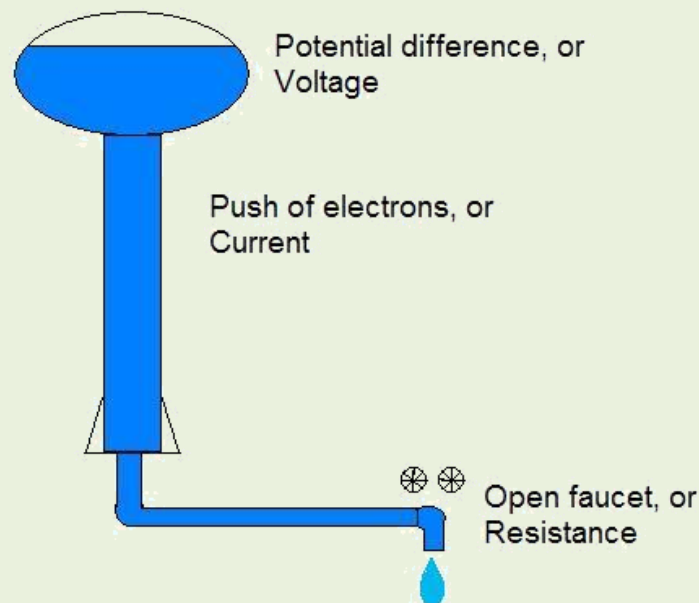
to the current. The voltage across the series then is the sum of the voltages across each. Resistors in parallel are connected end to end and have same constant voltage across the resistors.

Ohm's law states that the current (I) through a conductor between two points is directly proportional to the potential difference or voltage (E) across the two points, and inversely proportional to the resistance (R) between them.

The mathematical equation that describes this relationship is:

$$I = \frac{E}{R} \quad \text{or, } E = I \times R$$

I have always found this confusing. Here's a way that always helped me remember and understand Ohm's Law.



This is a water tower. Voltage is the amount of water in the tower. This is the potential difference between the positive and negative terminals. Current is the push of the electrons. Even though you may live close to the water tower and may have great push of water into your home you can control how much water is used in the shower by opening the faucet a little or a lot. This is the resistance to the flow.

Assuming the faucet was open completely the value of water in the tower would equal the push of water, just as without resistance the voltage equals the current.

Later, in the stimulator section we will use give an everyday example of Ohm's Law.

“AC” Alternating Current – Voltages or currents change polarity at certain intervals. AC current in electronics is when some voltage or current fluctuates with zero average value over a period of time as opposed to the DC which is the long term average value. AC is what is used in our homes, hospitals, etc. “DC” Direct Current, voltages or currents are a steady source flowing in one direction only. An example of direct current would be the flow of current from the negative to the positive terminal of a battery. In an AC circuit the hindrance to current flow is no longer called resistance, but rather impedance.

Electrodes:

For electrodiagnostic testing there are two types of electrodes used, surface and intramuscular. For a CMAP (compound muscle action potential), a recording electrode consists of two 1x1cm platinum or silver disk electrodes or the use of an adhesive electrode. Amplitude of a waveform will decrease with increasing the size of an electrode. An active G1 placed on the muscle of the nerve being tested and a reference G2 placed on a belly tendon. To record a SNAP (sensory nerve action potential) ring electrodes are placed longitudinally on the digit, along the nerve. The maximum amplitude of the response is affected by the distance between the two recording electrodes. Distances of three to four centimeters between active and reference electrodes are optimal.

Common filter settings for motor and sensory are as follows:

Sensory:

Low frequency (high pass) 20 Hz, High frequency (low pass) 2 or 3kHz
Timebase (Sweep speed) 1 or 2 msec/div and sensitivity is 10-20 $\mu\text{V}/\text{div}$.

Motor:

Low frequency (high pass) 2 Hz, High frequency (low pass) 10 kHz
Timebase 2 or 5 msec/div and sensitivity is 2-5 mV/div

Impedance:

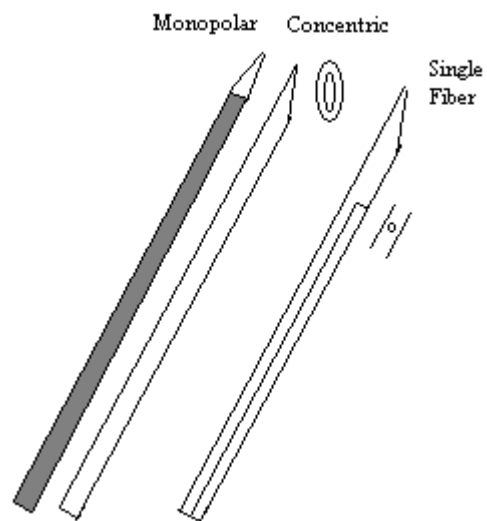
Input impedance in an AC circuit determines the current flow for a given alternating voltage source. Resistance that remains constant when the frequency of the voltage of the signal changes. In an EMG study, the circuit of the needle tip and input terminal become a voltage divider with changes occurring due to the impedance. Increasing the amplifier impedance higher than electrode impedance would decrease the loss of potential. Amplifier input impedances range from 100 kilohms ($k\Omega$) to many megohms ($M\Omega$). The higher the input impedance of an amplifier will improve the common mode rejection ratio. The common mode rejection allows more cancellation of unwanted signals and better resolution of physiological signals. In respect to recording electrodes, the higher the input impedance, the lesser effect of electrical asymmetry.

Whereas, higher electrode impedance increases amplifier noise and artifact. Broken wires are a source of external interference and waveform distortion.

Needle electrodes:

Sub-dermal needles are made of solid stainless steel with the lead wire made of copper and polyvinyl chloride insulation. The needle length is 12 cm and the gauge is 27. Sub-dermal needles come as a single needle or as a twisted pair, depending on the recording to achieve. The twisted needles are especially recommended for intra-operative monitoring recordings. This type of needle is useful when trying to minimize interference and artifact, due to the needle being flexible and easy to secure.

Intramuscular electrodes for routine EMG studies are either monopolar or concentric. A monopolar electrode is insulated except for the distal 0.2 - 0.4mm fine point and is made of stainless steel. The wire, covered by a Teflon sleeve has an average diameter of about 0.8 mm. A surface electrode or second needle must be placed as a reference, along with the ground. A monopolar needle tends to be less stable, allowing more noise. Impedance may range from 1.3 megohms at 10Hz to 6.6 kilohms at 10 kHz (Kimura p.42). A difference between a monopolar needle and a concentric needle is how they record. A monopolar needle tends to record potentials larger and more complex, while duration and firing rate stay the same.



A concentric needle is stainless steel with a wire in the center of the shaft. The wire tends to be made of silver, platinum or nichrome, measuring approximately 0.1 mm in diameter. The external rim measures approximately 0.3 mm with the pointed tip of the needle having an area of about $150\mu\text{m} \times 600\mu\text{m}$. The impedance may range around $50\text{k}\Omega$ (Kimura p. 42). A concentric needle has a smaller recording area since potentials are recorded between the wire and the shaft. Routine monopolar and concentric needle studies have a low frequency (high pass) filter of 20 Hz, and a high frequency, low pass 10 kHz. Time base is set at 10 msec/div and sensitivity 20 to $200\mu\text{V}/\text{div}$.

Single fiber EMG is used to record from single muscle fiber action potentials instead of motor units. The wire is much smaller, $25\mu\text{m}$ in diameter and mounted on the side of the needle. The single fiber needles may have two or more wires exposed along the shaft serving as the leading tip. Compared to monopolar and concentric, single fiber needles will show specific asymmetries. Single fiber EMG is best known for the use in neuromuscular junction disorders. Common filter

settings for single fiber needle studies are low frequency (high pass) 500 Hz or 1kHz, high frequency (low pass) 10 or 20kHz. Time base set at 0.5 to 1 msec/div and sensitivity 200 $\mu\text{V}/\text{div}$.

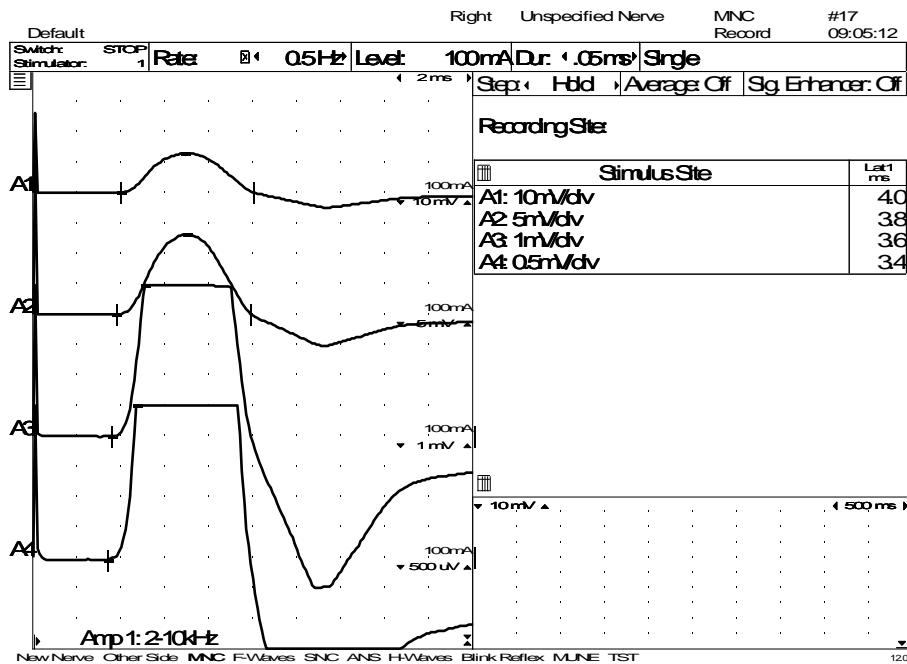
Amplifiers:

An amplifier is a device that increases the amplitude of a signal. In popular use, the term usually describes an electronic amplifier, in which the input “signal” is usually a voltage or a current. In audio applications, amplifiers drive the loudspeakers used in PA systems to make the human voice louder or play recorded music. In nerve conduction studies the input “signal” is a very small physiological signal from the nerve. Motor conduction studies are measured in millivolts (mV) and sensory conduction studies are measured in microvolts (μV). In EMG, the amplifier drives the recording instrument to display the signal on a monitor for analysis.

Amplification or the display of the amplified signal on the EMG instrument allows us to place values on the output, i.e. latency and amplitude. Amplification can be expressed as Gain or Sensitivity.

Gain is a ratio of the amplifiers’ output to input signal. Sensitivity is a ratio of input voltage to screen deflection in centimeters or millimeters.

Most important is using a fairly consistent sensitivity (or gain) setting because the onset latency of a motor response can appear quite different with different sensitivity settings as demonstrated here.



When performing serial studies from your own or another lab, settings such as these if different across studies, can lead to errors. This is especially true if you are using normative data from another lab.

Input impedance is a very important, but a very misunderstood principle of amplifiers. We all understand that relative low impedance at the electrode sites will demonstrate a better output quality, but this would not be true if the input impedance at the amplifier was not inversely high. This is because, as we learned by Ohm's law, the total voltage seen on the screen is greatest when the impedance at the amplifier is significantly greater than the electrode impedance. With the impedance significantly greater at the amplifier a mathematical unity will occur thus placing more importance on the electrode impedance. This math is demonstrated nicely in Dumitru's 2nd edition (pg. 78-79). The net result (because the unity of the input impedance) is an undesirable high impedance at the recording electrodes, which would result in smaller and distorted signals. This could be mistaken for axonal loss. Modern instruments have input impedances in the millions of Ohm's (M Ω).

A differential amplifier, as the name implies, magnifies the differences between the two inputs and cancels the common signals to both inputs. This happens because the second input is electronically inverted. Therefore, electrical noise from the environment should be eliminated because they would be the same to both inputs, but we know that is not the case, why? This is an example of real life as there are always differences between the two inputs and signals are never completely eliminated. Impedance differences, between the recording and reference electrodes, and using different types of electrodes (having different properties) are examples of input mismatch. These mismatched signals are presented differently to an amplifier, thus magnifying the differences instead of eliminating them.

Another confusing but important property of a differential amplifier is the Common Mode Rejection Ratio (CMRR). Simply put, this is the ratio of signals common to both inputs are amplified as compared to inputs that are different between the two inputs. This is important because external and unwanted signals, like electrical noise, are much larger than the physiological signals that we are most interested in. We want to amplify the physiological signal much more than we want to amplify the differences secondary to external causes. Modern instruments use CMRR of 100,000:1 (equal to 100dB) or higher.

Filters:

Biological signals from the human body are reproduced on our EMG instruments as waveforms that can be measured on both a horizontal and vertical scale. In reality there are many different and rapidly changing waves (or subcomponents of waveforms) and are either cancelled or summated to produce these waveforms. Some components of these waveforms have higher frequencies, for instance, the risetime and summit of the peaks. Some components are composed of slower frequencies, for example, the return to baseline. Some components are not desired,

such as slow sway of electrode movements, in the slower spectrum and amplifier noise in the higher frequencies.

The job of filters is to include the desired frequencies that make up the important components of the waveform while excluding the undesired frequencies outside the frequencies of interest.

A high-frequency filter (also called a low-pass filter) is designed to limit the amount of high-frequencies being recorded while allowing low frequencies to pass unaffected. The low-frequency filter (also called a high-pass filter) stops low-frequency components while allowing high-frequency components to pass.

The low-frequency filter removes or attenuates frequencies below the desired frequencies we want to record and removing these frequencies we change both measurements and shape of the waveform. When recording sensory nerve conduction studies the low filter is usually set to 20 or 30 Hz. If you raise this value, the onset latency would stay constant, but the peak latency would decrease and there would be a reduction in amplitude and area. The default low filter value for MNC is usually 2 to 3 Hz. Raising this value would have a similar effect where the onset latency would not change, but one would observe a reduction in amplitude and area.

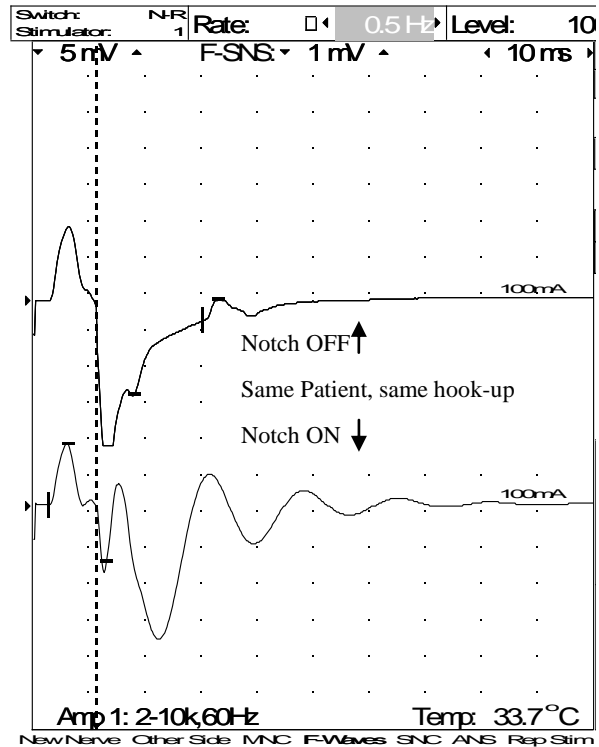
The high-frequency filter removes or attenuates frequencies above, or faster than the desired frequencies we want to record. Removing these frequencies, we change both measurements and shape of the waveform. When recording sensory nerve conduction studies, a high frequency filter of 2,000 to 3,000 Hz (2-3 kHz) is customary. If one were to reduce this value, increased latency and duration with amplitude and area reduction would be appreciated. While it is possible, but rarely done, additional increase of the HFF value in SNC recordings theoretically increase the amplitude and area while decreasing the latency and duration, but this is not as clear with the additional high frequency noise that is also recorded. When recording motor nerve conduction studies a high frequency filter of 10 or even 20 kHz is usually standard. If one were to reduce this value an increased latency and longer duration with amplitude and area reduction would again be appreciated.

This table reflects a simple mnemonic that makes remembering these rules easier. The original credit for this is unknown, but it is widely used especially when taking board exams.

	Amplitude/Area	Latency/Duration
HFF ↓ Do	↓ Do	↑ In
HFF ↑ It	↑ It	↓ Deed
LFF ↓ Do	↑ In	↑ In*
LFF ↑ It	↓ Deed	↓ Deed*
		* = only peak latency

Simply remember HFF goes first before LFF along the left (2 each), and then Amp and Area together go first and then Lat and Dur across the top in columns 2 and 3. Simply repeat “Do It, Do It, Do It, In Deed, In Deed, In Deed” (three times each) using the “D’s” for decrease and the “I’s” for increase, and place them in order top to bottom, left to right. You can easily see how the measurements and components are affected by the filters. For example if you want to see what happens to the amplitude if we increase the LFF, you could remember this table, draw it on a scratch pad, then answer Decrease as shown. This is easy to reproduce when taking examinations.

The notch filter removes only designated frequencies coinciding with undesirable frequencies. The most common undesirable frequency is the line frequency (60 Hz in North America, 50 Hz most of the rest of the world). The use of the notch filter is not usually necessary recording surface nerve conduction studies, especially after using care to achieve good recording impedances, but use of the notch filter is sometimes required during needle EMG. This is, at least in part, because the unlike properties of the electrodes (surface ground and/or reference and needle active). There can be signal distortion with the use of notch filters, seen here when recording F-waves (a ringing artifact) and sometimes when recording needle EMG. Use of the notch filter should be considered a last resort.



Sound

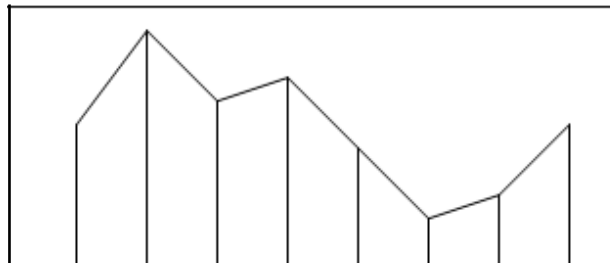
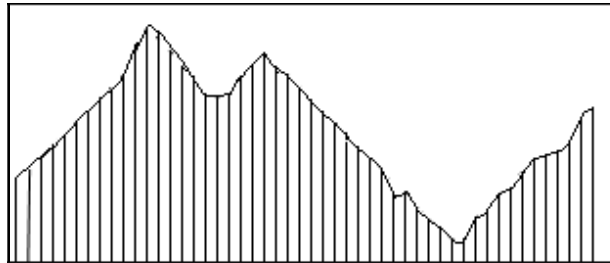
In nerve conduction studies we do not use the loudspeaker as much as the physicians do in needle EMG, but it can be useful listening to muscle artifact in the non-relaxed patient. It can be useful to have them listen to the artifact and ask them to make it go silent as they relax.

Analog to Digital Conversion:

The physiological signal is generated, picked up by the electrodes, amplified and filtered then displayed. Certainly a simple oscilloscope is adequate for this display, but in today’s computer world we want to change the appearance of the waveform, store it and sometimes print it, so a more sophisticated display is needed. We call this analog (oscilloscope) to digital (computer software and display) conversion, or taking the analog line, converting it to data points and redrawing it. This allows future recall and data manipulation and is a very powerful tool.

There are many other examples of digitization in our world. Remember the phonograph records some of us grew up with? We called them albums and some of us had hundreds. Well, today those hundreds of records converted to MP3 digital data would take just a small portion of space on an iPod. This is a perfect example of analog to digital conversion.

So, how many of these data points is enough to redraw and reproduce an analog line? On the horizontal line we look to sampling rate. The number of times per second the computer measures the analog signal and places a data point (a dot) on the screen. So, the higher the sampling rate (measured in Hz) the better the resolution of the trace. Too few points the line is choppy and misses small changes. See the examples to the right. Nyquist theorem states the sampling rate must be twice the highest frequency of interest. Today instrument companies provide



several multiples of the Nyquist frequency to allow maximum resolution. Values of 24-48 kHz (24,000-48,000 Hz) are not uncommon with today's systems. If the sampling rate is too slow, reproduction of the waveform will distort and there will appear to be fewer phases. This is called aliasing.

Data points on the horizontal line in relationship with sweep speed (timebase). Let us say there are 1000 data points across the horizontal line and we divide the screen into 10 equal divisions. There are 100 data points in each division. Which timebase setting would give you the finest resolution, 1 ms/div or 2 ms/div? Both would give 100 dots in that division, so 1 ms/div would give finer resolution and show minor changes in the waveform.

Vertical resolution from analog to digital conversion is expressed in bits or bits of resolution. A group of these bits is a byte, which to a computer is a numerical value. If an analog to digital converter has 12 bits of resolution it has the ability to resolve 2^{12} (4096) individual amplitude levels. So, if our sensitivity setting is at $20\mu\text{V}/\text{div}$ and we have 10 divisions and a maximal $200\mu\text{V}$ signal is recorded, we sample the amplitude (vertical scale) in steps of $0.049\mu\text{V}$ ($200\mu\text{V} \div 4096$ intervals). If we change the sensitivity to $10\mu\text{V}$ we can sample the same waveform on $0.024\mu\text{V}$ steps and see smaller waveform changes.

On both the vertical and horizontal resolution discussions it is important to note that instrument companies usually set these values and changing them during the recording is, most often, simply changing the display values. It is also important to remember while the manufacture's hardware and software gives us more than adequate default values; the monitors do not always

support as many points. In addition, the trace does not often use the entire screen. There has to be room on the screen for measurement tables and parameters, so even with high resolution monitors, not all data points are used for waveform display. While this was an important discussion when monitors had resolutions 320x180 (or similar) it is less important today as monitor resolution of 1600 x 1200 are common place.

Averaging:

Averaging is a valuable tool, especially for the small sensory responses. Averaging summates the traces together and divides by the total number in the average. In this way the random noise becomes smaller (averages out) while the time-locked event (low amplitude response) is preserved. The number of averages cannot be specifically defined and depends on the amount of background noise. Generally the number only needs to be sufficient to clearly define the desired signal.

There is a point when averaging that the signal is as good as it can be and the noise is as reduced as it can be, regardless if you were to continue averaging. The principle of Signal-to-Noise ratio defines that point. There is a nonlinear relationship between the number of responses and the S/N ratio. Let's say the signal you want to record is $2\mu\text{V}$ and the surrounding noise is $4\mu\text{V}$. The S/N ratio is 1 to 2, thus obscuring the signal. If you were to average 4 times the S/N improves to 1:1 (or simply 1), implying the signal is now the same size as the noise. Continue averaging 64 times improves the S/N ratio by a factor of 8, and the signal is 4 times that of the noise. This math is demonstrated nicely in Dumitru's 2nd edition (pg. 89). The bottom line is, if averaging is required it is best to leave the total number of averages open and observe the waveform no longer until such point it resolves adequately and no longer seems to improve.

Stimulators:

The stimulator has a cathode and anode. A cathode is an electrode through which electric current flows out of a polarized electrical device. In a device which consumes power the cathode is negative, and in a device which provides power the cathode is positive. In Nerve Conduction Studies cathode is negative in the electrical stimulator.

An anode is an electrode through which electric current flows into a polarized electrical device. In a device which consumes power the anode is positive, and in a device which provides power the anode is negative. In NCS the anode is positive in the electrical stimulator.

Stimulator properties

Voltage

Volt/Voltage: The volt is a fundamental unit of electrical measurement named after 18th century physicist Allesandro Volta, and a measurement in volts is referred to as voltage. Most of us encounter this unit of measurement when buying batteries such as the 9 volt (DC) battery. Inside

a battery there are two chemical reactions, which are separated from each other by a barrier. One of the reactions creates a surplus of electrons and the other creates a shortage of them. The electron surplus and shortage sides of the barrier are connected to the negative and positive terminals of the battery respectively. If given a pathway around the barrier, the electrons have the potential to do work to get from the negative to the positive terminal. The volt is a measure of this potential to do work. The volt is also referred to as a unit of electric potential.

Current

Current/Amp: Current happens when electrons travel from point A to point B. Direct current is what happens when you give the surplus electrons in the negative terminal of a battery a pathway to get to the positive terminal. The amp is the measurement of how many electrons per second are traveling through the pathway.

Ohm's Law – an application

The FDA limits the stimulus output voltage to 400 Volts. Let's assume we do not prep the skin – the skin resistance is 100 k Ω (100,000 Ω). What is the current delivered to the patient?

$E=IR$, or $400V=I \times 100,000\Omega$, restated is $I=400V / 100,000\Omega$. Thus, $I=0.004$, or 4mA is the actual current being delivered. It would be like trying to take a shower with the faucet only open 4%. It is possible, just not very easy.

A constant current stimulator (the default stimulator setting used by most instrument companies) will deliver the same amount of current and the amount of voltage will vary based on skin impedance.

Assume it takes 40mA to produce a supramaximal response. On the first stimulus the skin impedance is 5,000 ohms. Essentially, you have asked for 200 Volts ($40mA \times 5000\Omega$), and this is what the patient feels.

Let's say the skin impedance changes (i.e. less gel with successive stimuli) to 10,000 ohms. You are now asking for 400 volts ($40mA \times 10,000\Omega$), so the patient feels twice as much stimulus as before to achieve the same activation.

Duration: is the amount of time that the electrical stimulus is applied. Most instrument companies state stimulus duration in microseconds (μ sec) or milliseconds (msec). Over the years there has been much debate about what duration setting is best for the various nerve conduction modalities. There may not be a concrete answer to this question. Some authors start with a longer duration (i.e. 0.2 msec for MNC) while using less intensity, while others use a shorter duration (i.e. 0.05 msec for MNC) while using a more robust intensity.

Intensity is the unit of strength of the stimulus. It is stated as constant current in milliamps (mA) or constant voltage in volts (V).

Frequency is the number of occurrences of a repeating event per unit time. The period of a waveform is the amount of time it takes to repeat itself. The frequency is the inverse of the period, so we can use a simple equation to determine the frequency when we know the period:

$$F = 1/T$$

The term F is the frequency, measured in Hertz (Hz), and T is the period, measured in seconds (s). Since the period is one second, and $1, 1 = 1$, the frequency is also 1 Hz. As another example, if the period is 1/100 of a second, the frequency is $1, 1/100 = 100$ Hz.

Inadvertently reversing the cathode and anode changes the latency value of routine nerve conduction studies simply because the cathode is 2 to 3 centimeters further from the recording point. The distal latency may appear to be several milliseconds prolonged. Additionally, if you were to reverse the cathode and anode at the distal stimulation site, but use the correct cathode/anode orientation at the proximal stimulation site, a faster than actual conduction velocity would be recorded. Some authors believe reversing the cathode and anode will result in an artificially low amplitude as a result of anodal block. This is thought to be because the tissue near the anode is hyperpolarized preventing the action potential generated at the cathode from passing. Most of us do not subscribe to this theory because with normal and sufficient stimulation the anode can depolarize the nerve.

Stimulus artifact:

The electrical stimulus is received in the amplifier just as the NCS signal is received, except the stimulus is much larger. For this reason the amplifier can become saturated with the excessive potential. Most modern amplifiers recover from this overload in 5-10 milliseconds.

To reduce this stimulus artifact:

- Use short duration stimulus
- Use shielded electrode cables
- Prep the skin with alcohol or skin prep
- Remove callous with sandpaper
- Use electrode cream or gel
- Carefully place the ground electrode between stimulating and recording electrodes

Interference:

Not all electrical potentials registered during an EMG/NCS originate in muscle or nerve. Any voltage not attributed to the biologic potential sought represents an artifact or interference. These artifacts may mimic the indented signals sought during EMG/NCS examination.

Some examples that can cause interference during an exam are:

Amplifier Noise: Electrical noise inherent in an amplifier originates from all components, including the resistors, transistors, and integrated circuits. Operating the system at lower gains and with narrower filter band widths substantially reduces the noise seen on the screen.

Defective wires: The most likely cause of recording problems relates to a defect in one of the three recording electrodes. A broken wire induces bizarre and unsuspecting artifacts even if the wire appears intact.

Electrostatic and Electromagnetic interference: Sources of 50 or 60 Hz interference are common. Examples of these sources are electric fans, lamps, florescent lights, electric motors, light dimmers, and even unused power cords plugged into wall outlets.

Electrical Safety:

All personnel involved in recording bioelectric potentials should be knowledgeable about electrical safety. Electrical safety recommendations are concerned with detecting or preventing dangerous situations. Violating safety standards or neglecting inspections could invalidate insurance coverage or accreditations. If an accident occurs, individuals or institutions could face charges of negligence or malpractice. In addition, some of the measures intended to ensure safety also reduce artifacts and interference in the recording.

The standards and recommendations on electrical safety have changed frequently. Electromyographers and staff should understand not only the most current regulation but also the theory of electrical safety.

- The instrument must be plugged into a hospital grade, 3-prong outlet
- All cables and power cables should be tightly connected
- Examine all power cords and other cables for fraying or damage
- Comply with hospital required safety checks and leakage current testing (usually every 6 months or annually)
- Only one ground to prevent ground loops
- Keep patient extremities away from metal pipes, rails and machinery that could act as an additional ground
- Never power the system up or down while the patient is connected
- Care must be used when working with patients with pacemakers and indwelling defibrillators. Do not perform proximal studies on that limb and keep pulses short, low and slow.
- Keep your electrodes clean
- Read and follow the operator manual requirements

Bibliography:

Ambu® Neuroline Subdermal, Description page.

[http://www.ambu.com/COM/Patient_Monitoring - Diagnostics/Patient Monitoring -
_Diagnostics.aspx?GID=GROUP52&ProductID=PROD299](http://www.ambu.com/COM/Patient_Monitoring_-_Diagnostics/Patient_Monitoring_-_Diagnostics.aspx?GID=GROUP52&ProductID=PROD299), August 23, 2010.

Dumitru, Daniel, Anthony Amato and Machiel Zwarts. "Electrodiagnostic Medicine." 2nd Ed. Hanley and Belfus, Philadelphia. 2002.

Kimura, Jun. "Electrodiagnosis in Diseases of the Nerve and Muscle, Principles and Practice." 3rd Ed. Oxford, New York, Philadelphia. 2001.

Lindsay, Andy. "Basic Analog and Digital." Parallax, Rocklin, CA. 2003.