Fundamentals of Electronics

Directions for nursing CEU credit: Review the material in this module. Download the test form. Take the test. Fax or send the answer sheet with a form of payment. Passing score is 75%. You have 3 chances to take the test. Upon completion you will receive a CEU certificate. Critical Care ED is an approved provider of continuing education in nursing by the California Board of Nursing.

Module objectives: Upon completion of this module the learner will be able to:

Identify various electrical quantities and their measurement
Explain Ohm's law and the relationship among all of its components
Apply Ohm's law to clinical practice
Explain the concepts governing resistors, capacitors, inductors
Explain the role of impedance in pacemakers and with radiofrequency ablation
Discuss the principles of electrode recordings

I. Basic Quantities

Basic quantities are terms and concepts of electronics upon which the understanding of all is based. Therefore, it is crucial to have a good understanding of these terms. These are terms we use every day though often with just a vague idea of how they're defined.

Current

Current is considered the first quantity which is of major importance. Current is about flow, flow of positive charge. It is the flow of electrons in a completed circuit. In a pacing system, current is measured in **mA** (**milliamps**, represented by the letter '**I**'). The milliamperage is determined by the number of electrons that actually move through a circuit. The greater the number of charges flowing through a surface at a given time, the greater the current will be.

One application of the term 'current' would be used in the designation **'constant-current' pacemaker**. Such a pacemaker would deliver a current level that would not vary during stimulation. The majority of pacemakers have a voltage and current level which decrease during stimulation.

A **'constant-voltage' pacemaker**, on the other hand, is a pacemaker which has a capacitor-like output circuit, and discharges through the pacing lead. During stimulus delivery, both voltage and current decrease or decay.
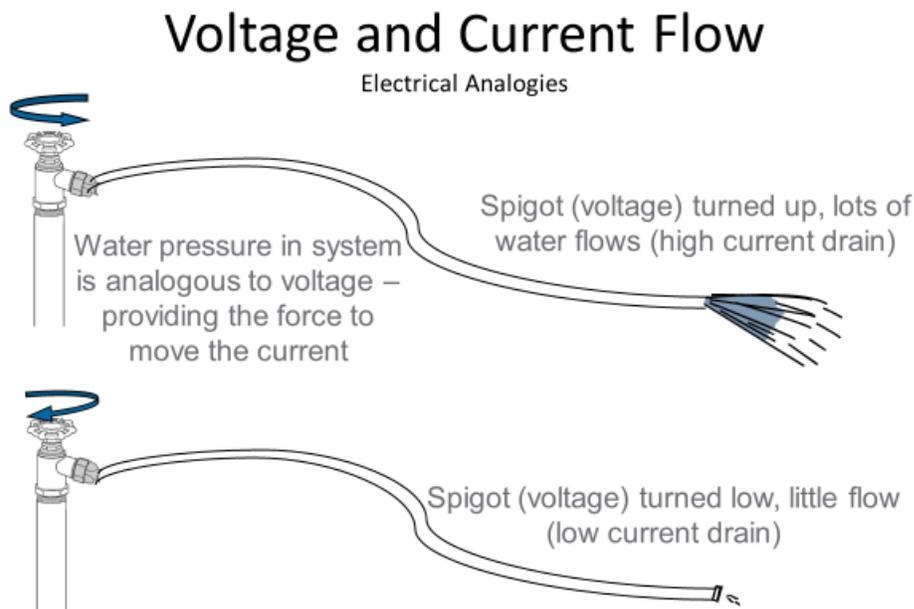
Voltage

When we speak of voltage, we speak of pressure. Voltage is the electrical potential energy per unit of charge. One **volt** = 1 **Joule** per **Coulomb.** Voltage is a component of **Ohm's law**. This electrical potential energy must have an origin and a destination. The force or 'push' provided by voltage causes electrons to move through a circuit. In a pacing system **voltage** is represented by the letter '**V'.**

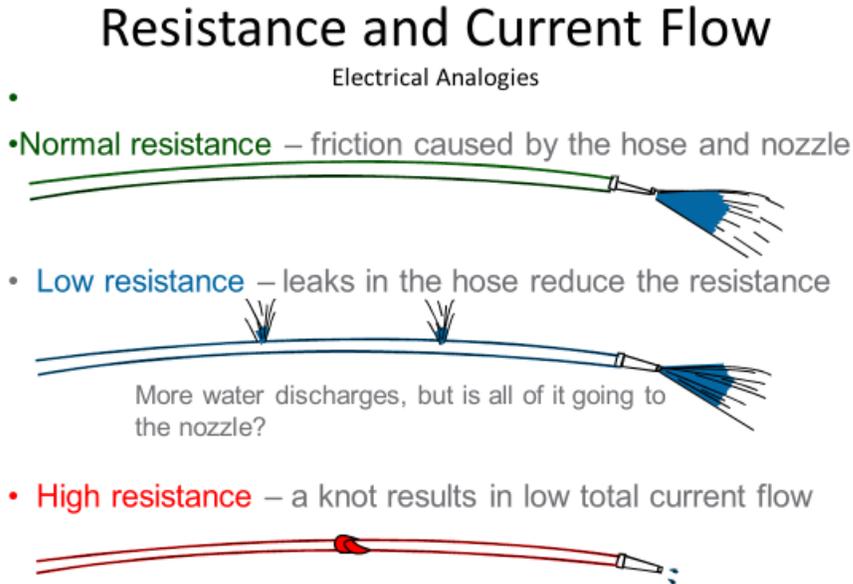**Relationship of Voltage and Current**

Voltage and current are related to each other by **resistance.** The amount of current delivered is controlled by the resistance that exists in a system. If resistance is higher, less current will flow. If resistance is lower, more current flows. It is this relationship that Ohm's law represents. In pacing we often replace 'resistance' with 'impedance'. **Impedance** can be defined as opposition to flow (to be discussed in greater detail later). In a pacing system, impedance is measured in ohms, represented by the letter 'R" or Ω. Impedance is the measurement of the sum of all resistance to the flow of current.

One of the best analogies for explaining (and remembering) this is to think of water flowing through a hose. Voltage is the force, current is the water, and the hose or the pacemaker lead represents total impedance. The nozzle of the hose would be the electrode, while the tubing would be the lead wire.

Voltage and Current Flow
Electrical Analogies

Water pressure in system is analogous to voltage – providing the force to move the current

Spigot (voltage) turned up, lots of water flows (high current drain)

Spigot (voltage) turned low, little flow (low current drain)

To take this discussion a bit further we can think in terms of various resistance related situations. With normal resistance we would see 'good' and supposedly adequate flow. Low resistance however could occur if there were holes in the hose or, in the case of a pacing lead, an insulation defect, either situation allowing leakage (of water or of current). High resistance, on the other

hand, could occur because the hose is tied in a knot or because there is a lead fracture. Each of these situations would lead to a low current flow situation. The illustration below shows this.

Resistance and Current Flow
Electrical Analogies

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•Normal resistance – friction caused by the hose and nozzle

• Low resistance – leaks in the hose reduce the resistance

More water discharges, but is all of it going to the nozzle?

• High resistance – a knot results in low total current flow

Ohm's Law describes this relationship

$$I = V/R$$
$$V = I \times R$$
$$R = V/I$$

I = amperes (A) (current)
V = volts (V) (voltage)
R = ohms (Ω) (impedance)

If the voltage (V) is reduced by half, the current (I) is also cut in half. This is like turning the pressure back on the faucet and decreasing water flow.
If you reduce the impedance (R) by half, the current (I) doubles. If you remove calcium buildup in your water pipes or faucet, water flow increases.
If the impedance (R) increases, the current (I) decreases. Increased buildup leads to decreased flow.

This formula becomes useful with pacemakers when trying to determine generator settings.

Charge

Charge is a basic electrical quantity that, in most instances, is referring to the flow of 'positive' charge. In actuality it is a situation of either an excess or lack of electrons. Charge is measured in coulombs (**REMEMBER: 1 Volt = 1 joule/coulomb**). (When you're trying to remember the unit for 'charge' think '**9 VOLT battery'**).We encounter the concept of charge daily, whether it be in examining the + and – poles of a battery or in looking at the sign designated for electrolytes in the body. We contemplate 'charge' when thinking of th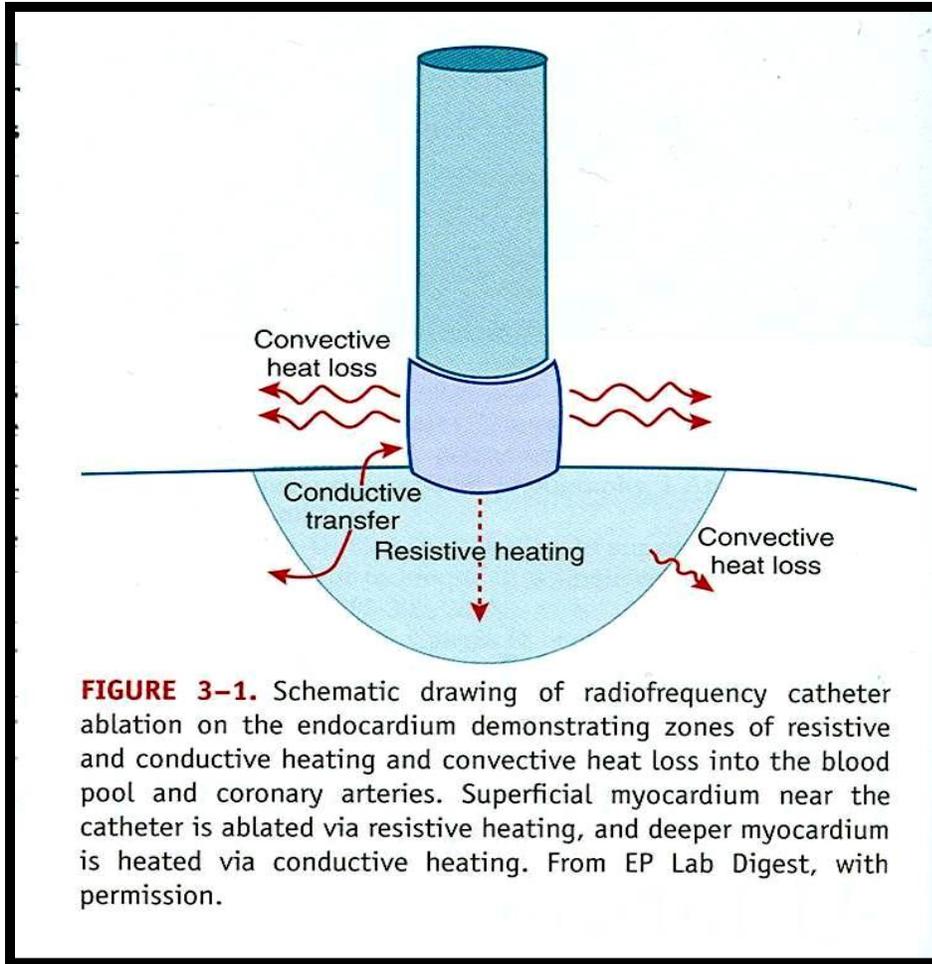e electrode tip of a pacing lead. **Polarity**, therefore, also plays a role in charge. Polarity must be positive or negative.

We cannot create or destroy charge. Charge leaving a battery as current is balanced by that which returns to it.

Energy

Energy is measured in joules. A **joule = 1 Newton x 1 meter** (force times distance). Energy occurs when a charge is moved against electrical forces. Potential energy is gained in this process, as is, therefore, the ability to do work. (Defibrillation energy is measured in joules.)

Electrical energy can also become other types of energy. An example of this is the production of **radiofrequency** energy during **ablation**, which is then converted into thermal energy by tissue, producing a burn. **Resistive heating** is what occurs with tissue just beyond the catheter tip. An impedance change occurs between the metallic electrode (low impedance) and the tissue (high impedance). This tissue area becomes a source of radiant heat, and tissue damage occurs. Meanwhile, the resistive heating gives rise to conductive heating, the second phase. Heat transfer to adjacent areas occurs. This causes tissue destruction. **Conductive heat** transfer is sensed by a thermistor probe in the catheter tip. This is tip temperature monitoring.

FIGURE 3–1. Schematic drawing of radiofrequency catheter ablation on the endocardium demonstrating zones of resistive and conductive heating and convective heat loss into the blood pool and coronary arteries. Superficial myocardium near the catheter is ablated via resistive heating, and deeper myocardium is heated via conductive heating. From EP Lab Digest, with permission.

With pacing, you are able to calculate energy if you know what the stimulus voltage, current, and duration are (if the voltage and current remain constant throughout the stimulation).The formula is

$$E = VIT$$

$$E = \text{energy}$$
$$V = \text{voltage}$$
$$I = \text{current}$$
$$T = \text{stimulus duration}$$

This formula can be applied in the following way: if the pacing voltage is known, the current will be entered in milliamps (mA) and the stimulus duration will be reported in milliseconds (ms). The resulting energy unit will be microjoules (μJ). This calculation will not be correct however if voltage and current are not held constant throughout the stimulus delivery.

Power

This is a measure of the rate of energy conversion for a system. Power is measured in watts:**1 watt = 1 joule/sec**. **Ablation power** is delivered in **watts**. Power is a product of current and voltage if current and voltage are constant. Power delivered is determined by the product of voltage and current drain within a system. Power is measured by a wattmeter. Formulas for power:

$$P = VI \qquad\qquad P = \text{power}$$
$$P = I^2R \qquad\qquad V = \text{voltage}$$
$$P = V^2/R \qquad\qquad I = \text{current}$$
$$R = \text{resistance}$$

Self-Study Questions:

1. Provide an analogy to describe 'current'.
2. In what unit is current measured?
3. Describe voltage.
4. Discuss the relationship between current and voltage.
5. State the components of Ohm's law.
6. What is the equation for Ohm's law?
7. Describe what is meant by 'charge'.
8. What is the unit of measure related to charge?
9. When does energy occur?
10. What is the unit of measure for energy?
11. What is the unit of measure used for ablation energy?

II. Derived Quantities, Units of Measure, and Components of a Circuit

This section integrates information about circuit components, their function, and how their units of function are measured. Derived quantities are measurable electronic quantities that are determined through a mathematical manipulation of basic quantities. Examples would be current density, resistance, capacitance, and impedance.

Resistor

A **resistor** is a two-terminal electronic-circuit component where the current flow is proportional to the applied voltage described by Ohm's law. A resistor produces a voltage drop between its terminals in proportion to the current. In the formula $V = I/R$: R is the voltage drop V across the resistor divided by the current I through the resistor. Resistors are part of an electronic circuit.

Resistance is the property of an electronic-circuit component, a resistor. In resistance, current flow is proportional to applied voltage measured in Ohms.

e.g. for V = I/R, if V = 5 volts, and R = 1K, current flow (I) will be 5 mA

Resistivity is a material's property of resistance

Capacitor

A capacitor stores electrical potential energy in an electric field. The capacitor holds positive and negative charges apart from each other. This energy is measured in **Farads.** A farad is equal to 1 coulomb per volt.

Rapidly-varying signals will pass through a capacitor more easily than slowly-varying signals.

Capacitance is the storage process. It is the ability of a structure to hold an electrical charge. Capacitors which are used in some electronic circuits are storing energy smaller than a farad. These smaller amounts could be called: millifarad (mF), microfarad (µF), nanofarad (nF), and picofarad (pF), which is also referred to as a 'puff'. Cell membranes are excellent examples of capacitors.

The formula for capacitance is: C=Q/V

> C= capacitance
> V= voltage between plates
> Q refers to the charges between 2 electrical plates

(assuming this is a 2-plate capacitor, a common type of
         storage system)

If the geometry of the conductors and the dielectric properties of insulators between the conductors are known, capacitance can be calculated. An exception to this would be when ferroelectric materials such as iron are used. Iron can be magnetized; therefore the geometric formulas would be altered.

Battery capacity is measured in ampere-hours (units of charge). Battery depletion leads to an increase in internal resistance. When this occurs, the ability to charge becomes limited.

Inductor

An inductor stores electrical potential energy in a magnetic field, usually in the vicinity of a conductor through which electrical current flows. Inductors often consist of a coil of wire. The ability to store magnetic energy measured by inductance is in units called **Henrys.** Slowly varying signals will pass through an inductor more readily than a rapidly varying signal (opposite of capacitor). **Inductance** is the process by which the energy is stored. An inductor performs like a combination of inductance, some resistance that is wire related, and some capacitance.

Impedance:

Impedance is opposition to current flow through a substance, measured in ohms. It is a combination of the effects of resistance, capacitance, and inductance in opposition to current flow. It is different from resistance though in pacing the terms seem to be used interchangeably. Impedance is a determinant of battery longevity if lithium iodine batteries are used. With the use of Ohm's law in pacing, impedance is substituted for resistance.

In pacing, impedance is determined by: conductor resistance of the lead, the resistance to flow of current from the electrode to the tissue, and all the changes of opposite polarity in the heart at the interface, or conductor resistance, electrode resistance, and polarization impedance. Decreasing lead radius tends to minimizes current flow

Normal pacing impedance is ~ 500 ohms; with an insulation defect, that may drop to < 250 ohms; with a lead fracture, > 1000 ohms. With an insulation defect, current can leak easily, thus little 'resistance' is recorded; with a lead fracture, current cannot reach its destination easily, and impedance is extreme. The higher the impedance, the lower the flow and vice versa. Lead impedance is measured to assess the integrity of a pacing system.

Some high impedance electrodes are being used these days, as they have a smaller surface area, and therefore current is more dense. This decreases current drain from the battery.

Impedance is measured during RF ablation. Tissue heating to > 50 degrees centigrade while delivering RF has been associated with impedance falls of 5 to 10 Ω. Impedance drops of > 10 Ω have been correlated with coagulum formation and subsequent impedance rises. Impedance fall of 5-10 Ω indicates tissue heating. When impedance rises during RF ablation, current delivery decreases and is associated with boiling, popping, char, coagulum, and clot formation.

Some RF generators have continuous impedance monitoring built in; this is helpful with patients with unusual anatomy or when there is difficulty determining the exact location of the catheter. When a catheter is in contact with blood, impedance is lower than when it is in contact with tissue.

Another method used to check for tissue contact is to deliver a 2 W RF application to tissue before ablation. A higher impedance value is registered with firm contact than with poor contact. Contact force sensing plays a role here.

Also, impedance monitoring is helpful when using cooled or irrigated tip catheters as tip temperature feedback is inoperative with these catheters.

Diodes, Zener Diodes:

A **diode** is a circuit component that limits current flow to a single direction. This occurs because there is a high resistance to current flow in one direction, and low resistance to flow in the other direction. A **Zener diode**, however, allows current to flow in the normally inhibited direction when the applied voltage exceeds a certain value. An example of this would be during external defibrillation. Current is shunted past a pulse-generator's circuits preventing damage to the circuits. However, current is instead shunted toward the pacing lead. The result of this may be the production of dangerously high current density at cardiac electrode/tissue interface.

What are the components of a circuit?

A circuit is a closed path which is formed from the connection of electrical components. Electrical current is able to flow through a circuit. Components of the circuit could be resistors, capacitors, inductors, leads and tissue.

Self-Study Questions:

1. What are derived quantities?
2. What is capacitance?
3. What is inductance?
4. How do capacitance and inductance differ?
5. What is the unit of energy measured for capacitance and for inductance?
6. What is a resistor?
7. Discuss impedance in both pacing and ablation.
8. What is a diode and a Zener diode?
**9. What are the components of a circuit?**

III. Signal Concepts

What about signals? We see signals as the final product on our tracings. Signals are time-varying voltage, e.g. intracardiac-electrogram voltage. Signals are processed by pulse-generator sensing circuits. A discussion of electrode recordings follows.

Principles of Electrode Recordings

The electrode pair

An electrogram, a term originally coined by Waller (late 1870's) in reference to deflections of the surface ECG, represents the timing of arrival of an impulse at a particular site within the heart where a recording electrode pair is located. This pair of little exposed metal surfaces near the tip of a catheter functions identically to the two skin electrodes used in the recording of a rhythm strip, lead II for example. The only difference is that they are located inside the heart and are positioned alongside each other instead of on the body surface separated by a couple of feet. One electrode is arbitrarily positive while the other is negative. In effect, they are the red and black probes of an ordinary voltmeter. When placed in or near an area undergoing a change in charge -such as that occurring at the leading edge of a wave front of activation (the front of the impulse)- the electrode pair and the recording amplifier system (the voltmeter) they're hooked up to- provide a real time registration of the transient voltage change which indicates our wave front has just arrived at our recording site.
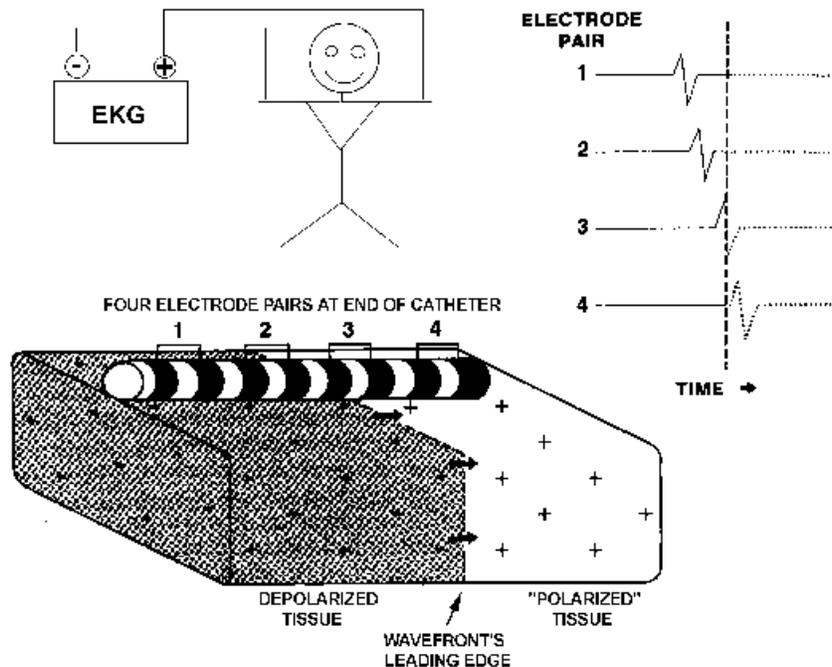
Leading edge of activation

Interelectrode distance

The greater the interelectrode distance, the larger the "field of view" of the electrode pair responsible for the recorded signal and the larger and more complicated the electrogram appears. **Wide** spacing is usually undesirable because, like a wide-angle lens, it includes more information in the picture than is desirable. Since we are primarily interested in precise timing of activation of a wave front arriving at a particular site, we wouldn't want to see what is going on several centimeters away. If you do, then you should make arrangements to have an electrode pair there, too. **Narrow** interelectrode distances on the order of 2 mm provide a well "focused" view of a small area of tissue surrounding the electrode pair. This allows for one to more easily discriminate activation in one region from an adjacent area. On the other hand, it sometimes may be necessary to use wider spacing because that may be the only way to "see" a nearby structure's activation which is otherwise inaccessible.

Electrode spacing

The left-hand electrogram above was recorded with 10 mm (wide-spaced) interelectrode distance. Remote (unwanted) ventricular activation can be seen. The right-hand electrogram was recorded with 2mm spacing. It is a cleaner signal making its timing of onset easier to measure (see "measuring the intervals" below). Both signals are recorded at 100 mm/sec and at the same gain. If you turned the gain down, say by a factor of 2 or 5, the electrogram on the right (close-spacing) would be even easier to measure onset while the one on the left (wide spacing) would retain its multiphasic, untidy appearance.
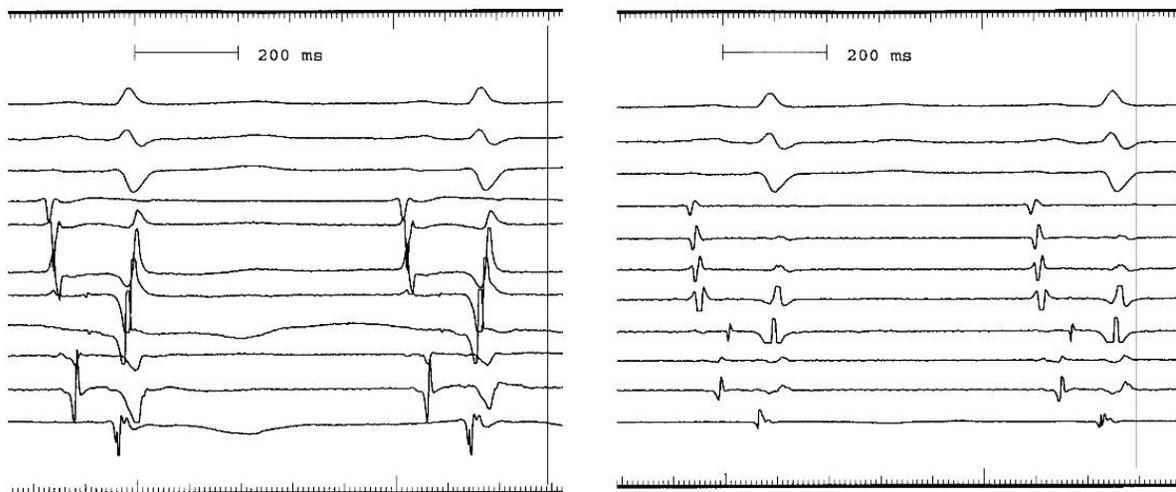
Filtering

A bioelectric signal such as the one representing electrical activation of the heart contains many different frequencies, some more heavily represented than others. The high frequency content of the signal represents the rapidly changing portions (QRS complex) while the low frequency content consists of slow waveforms (T wave). This is true whether the signal is being recorded from the body surface (ECG) or from inside the atrium or ventricle (electrogram). By filtering the signal, we can choose which frequency content that best reflects what is going on during each depolarization.

It is desirable to reject the low frequency content because the EP study primarily concerns itself with depolarization of the heart and the relative differences in timing of activation comparing one region to another. Thus, repolarization signals are to neither be seen nor heard. Another reason to reject lower frequencies is to eliminate wandering baseline, commonly seen on the ECG channels since it, too, is a low frequency event. A *high* **band pass filter** is used to accomplish this. It allows passage of those frequencies *higher* than a given cutoff on the display. Stated

another way, it rejects those below the cutoff.   A typical cutoff is 30Hz so that everything below 30 cycles per second (the slow stuff) is rejected.   Undesirably high frequencies will also be eliminated by a *low* **band pass filter** since they may not contribute useful information or because they can't be faithfully reproduced anyway (most signals nowadays are digital, not analog).   A cutoff frequency, often 500 Hz, is used to reject everything above that value. Stated another way, a low band pass filter allows passage of frequencies *lower* than the cutoff value.

Thus, the end product is the middle ground signal with frequency content **between** 30-500Hz. The desirable frequency content of the intracardiac electrograms will be found within this range. Note that if the high band pass filter cutoff was *raised* to 100 Hz instead of 30 Hz, the infamous 60 Hz interference would be eliminated. Sounds like a great idea! The reason we don't use this cutoff is not because we're inviting 60Hz; rather we're trying to avoid the loss of *gain* in the signal that would accompany a higher cutoff.

The following tracings illustrate the consequences of *including* low frequency content vs *rejecting* it by using a high band pass filter of 0.5Hz (left tracing) instead of the usual 30 Hz filter (right tracing).


Frequency content

The left-hand tracing shows how the lower frequencies (T wave) are let in due to the excessively low cutoff of 0.5 Hz. They're eliminated when this cutoff is increased to 30 Hz. Low band pass filtering differences are not shown because the difference is not as impressive.

Clipping

Clipping refers to the rejection of a signal above a given *voltage* (positive or negative). Thus, the excursion of the signal being displayed is limited in how far it can travel above or below baseline.

The effect is to eliminate the untidy and confusing overlap that would exist between adjacent channels. The "limiters" were turned off in the left-hand tracing (below) causing channel tracing "overlap" while the right-hand tracing is clipped and ready for show.
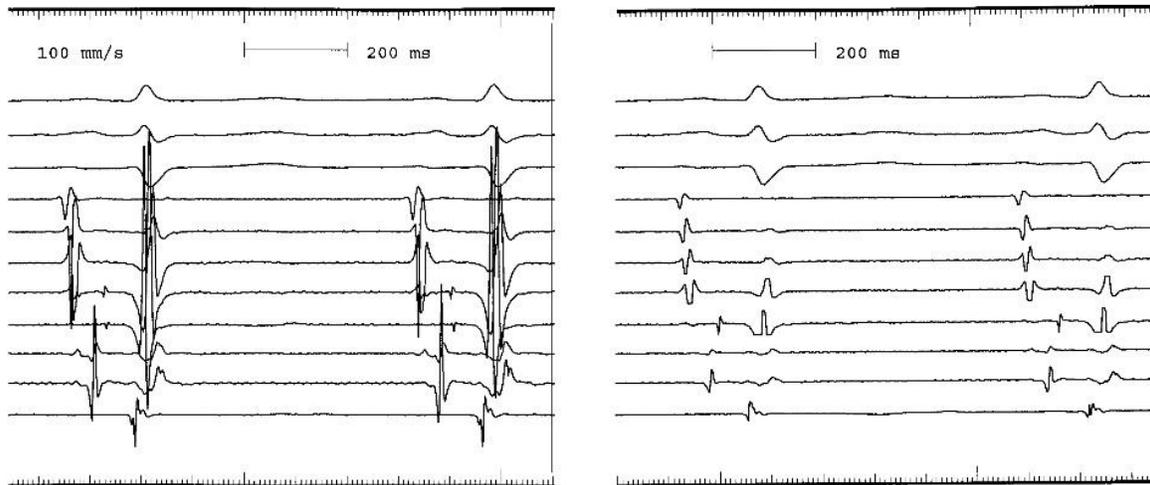
Clipping

Amplifiers

An amplifier is any device that changes the amplitude of a signal. The signal is usually voltage or current. Amplifiers increase the height or amplitude of a signal without changing any other component. The signals obtained from the surface and intracardiac electrodes are usually <10 mV in amplitude. As a result, amplification must occur before the signal can be digitized. After this the signal can be displayed and then stored. An effort must be made to eliminate extraneous signals from the beginning. Proper skin preparation prior to applying skin electrodes is a part of this. Current leakage should be avoided and there must be proper grounding and shielding.

Self-Study Questions:

1. Discuss signal maximization.
2. Define various types of filtering.
3. What is clipping?
4. What is an amplifier?
5. What is the role of amplification in signal processing?

Further reading (amazingly) Wikipedia articles on Ohm's law and Electrical resistance conductance.

References:

Boylestad R, Nashelsky L: *Electronics*. Englewood Cliffs, NJ, Prentice Hall, 1996.

Ellenbogen K, & Wood, M: *Cardiac Pacing and ICDs*. Malden, Blackwell, 2008.

Ellenbogen K, Kay N, Lau C, Wilkoff B: *Clinical Cardiac Pacing, Defibrillation, and Resynchronization Therapy.* Philadelphia, Saunders, 2007.

Haines D, Verow AF.: Observation on electrode-tissue interface temperature and effect on electrical impedance during radiofrequency ablation of ventricular myocardium. *Circulation* 1990;82:1034-1038.

Hartung WM, Barton EM, Deam AG, Wolter PF, McTeague K, Langberg JJ. Estimation of temperature during radiofrequency catheter ablation using impedance measurements. *PACE* 1995;18:2017-2021.

Hayes DL, Lloyd MA, Friedman PA. *Cardiac Pacing and Defibrillation: A clinical Approach.* Armonk, NY; Futura, 2000.

Mackey S, Thornton L, He D, Marons FI: Frequency dependent impedance measurements: An indicator of catheter contact. *Circulation* 1993; 88(4) abstract: I-400-2150.

Moulton K. *Order and Disorder in the Cardiac Rhythm: The Basics*. Springfield, IL: Critical Care ED, 2005.

Murgatroyd F, Krahn A. et al. *Handbook of Cardiac Electrophysiology*. London: ReMedica, 2002.

Schurig L, Gura M, Taibi B. *Educational Guidelines: Pacing and   Electrophysiology, Second Edition*. Armonk, NY:Futura , 1997.

Strickberger AS, Vorperian VR, Man KC, Williamson BD, Kalbileisch SJ, Hasse C, Morady F, Langberg JJ. Relation between impedance and endocardial contact during radiofrequency catheter ablation. *Am Heart J* 1994;128:226-229.

Strickberger AS, Ravi S, Daoud E, Niebauer M, Man KC, Morady F: Relationship between impedance and temperature during radiofrequency ablation of accessory pathways. *Am Heart J* 1995;130:1026-1030.

Strickberger AS, Weiss R, Knight BP, Bahu M, Bogun F, Brinkman K, Harvey M, Goyol R, Daoud E, Man KC, Morady R. Randomized comparison of Tow techniques for titrating power during radiofrequency catheter ablation of accessory pathways. *J Cardiovasc Electrophys* 1996;7:795-801.

http://en.wikipedia.org/wiki/Capacitance