I BASIC NEUROPHYSIOLOGY

Chapter 1

Basic Electronics and Physics

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DIRECT CURRENT ELECTRICAL CIRCUIT CONCEPTS
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LOW-PASS AND HIGH-PASS CIRCUITS
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APPLICATION TO ELECTROPHYSIOLOGY

Certain basic electrical and physical principles underlie the theory and application of clinical neurophysiology. These principles dictate the manner in which electrical signals behave in physiological tissues and govern the manner in which these signals can be measured. Basic concepts are necessary for the understanding of two main aspects of this discipline. An understanding is required of the nature of the physical, chemical, and biological processes that produce neurophysiological phenomena. Secondly, an understanding of the instrumentation and recording techniques is required to make neurophysiological measurements.

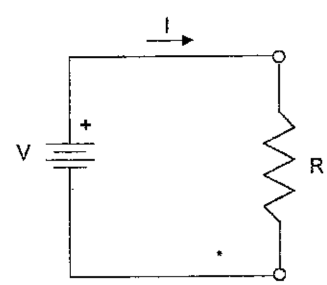
The major challenge of measuring such phenomena rests in the amplification of minute physiological signals. The following discussion emphasizes the fundamental concepts that are common to all areas of clinical neurophysiology, and provides a foundation for understanding neurophysiological processes in specific settings.

DIRECT CURRENT ELECTRICAL CIRCUIT CONCEPTS

From physics, we know that electric current in a conductor consists of the flow of electrons in response to an applied electrical potential. The amount of current depends on the size of the electrical potential and the resistance of the conducting medium. Many conductors are metals, which have a natural abundance of free electrons due to their atomic structure. Current can also flow in solutions or living tissue, by virtue of the ionic processes that produce free electrons, or a loose molecular structure that sheds electrons. Insulators are materials that have very few free electrons and, hence, conduct very little current.

In certain circumstances, such as conduction of muscle or nerve potentials through body fluids, current can also be conveyed by ions in a tissue or solution, rather than by electrons. Figure 1–1 illustrates the basic representation of a constant (direct-current, or DC) voltage source, connected to a resistance, resulting in the flow of current.

Potential can be considered a force that causes the movement of charged particles. Potential exists whenever uneven charges exist in a material, producing a potential difference. Even though the net charge may be zero, whenever charges are unevenly distributed, there will be nonzero potentials in association with the charge distribution. Electrons have negative charge. In a potential field, they will flow from a point of negative charge to a point of positive charge. This is because they are both repelled by the negative charge and are attracted by the positive charge. Even though current is carried in this way by negatively charged electrons, it is the convention to describe current as flowing from positive to negative. Thus, the current is said to flow in a direction opposite to the electron flow. The flow of current, if constant, can be written as $I = Q/t$, where Q is the quantity of charge, and t is the time in which is transferred. The basic unit of current, the ampere, is defined as one coulomb of charge per second. The coulomb is defined as follows: 1 coulomb $= 6.24 \times 10^{18}$ units of charge, where an electron has one unit of negative charge. Whenever current flows in response to the potential difference, it meets with resistance to the flow, which limits the flow to a particular value. The voltage difference across the resistance is known as the voltage "drop" across it. In general, Ohm's law specifies the



voltage: V (volts)
current: I (amperes)
power: P (watts)

$$V = I \times R$$

$$I = V / R$$

$$P = V \times I = (I \times R) \times I = I^2 \times R = V^2 / R$$

FIGURE 1–1. A DC voltage source, *V*, connected to a resistor, *R*, results in a current, *I*, flowing out of the voltage source and through the resistor. The relationship between voltage and current is given by Ohm's law, $V = I \times R$, and the power is the product of the voltage and the current.

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relation between these as $V = I \times R$, where V = voltage in volts, I = current in amperes, and R = resistance in ohms (Ω). Thus, for example, if a 5-volt drop exists across a 30-Ω resistance, the current will be $I = V/R = 5/30 = 0.167$ amperes.

In common terminology, the positively charged terminal of a battery is called the anode. The negatively charged terminal is called the cathode. Since the cathode is negatively charged, it has an abundance of electrons. If a resistance is provided from the anode to the cathode, electrons will flow from the cathode, through the resistance, to the anode, and we say the circuit is closed. By convention, the current is said to flow from the anode, through the resistance, to the cathode. If the resistance is removed or increased to a very large value, we say the circuit is open, and no current flows. If an effectively zero resistance is provided so that current is limited only by the battery itself, we say there is a short circuit.

Energy in electricity is associated with the amount of charge and the size of the electrical potential, so that $E = Q \times V$. Power is the rate of transfer of energy. Since the rate of transfer of the charge is simply the current, electrical power is simply the current times the voltage: $P = E/T = Q \times V/T = (Q/T) * V = I \times V$. The power in an electrical signal, expressed in watts (W), is defined as the product of the voltage and the current. As such, we can have either DC power or AC power.

Example:
If 2 milliamperes pass through a load of 100 Ω, the power is $E = 0.002 \times 100 = 0.2$ W = 200 milliwatts (mW).

Electrical quantities are expressed as voltage, current, resistance, and related values. Often, however, what is important is not the numerical value of some measurement, but its proportionality to another value, or the ratio of the values. Ratios can be expressed either as direct ratios (e.g., 20:1), as a percentage (e.g., 5%), or as decibels, abbreviated as dB.

Power Ratio (dB) = 10 x log10 (P_2 / P_1)

Given amplitudes A_1 and A_2:

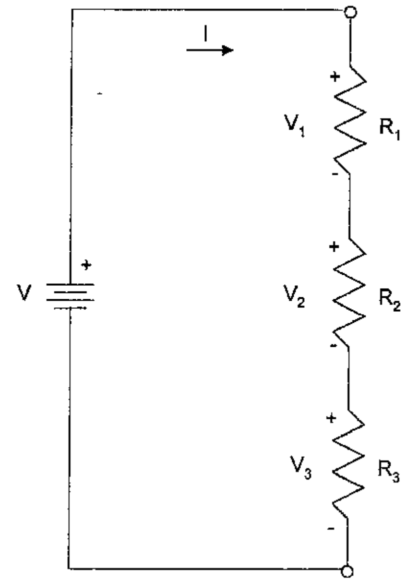
Amplitude Ratio (dB) = 10 x log10 (P_2 / P_1)

Amplitude Ratio (dB) = 10 x log10 (A_2^2 / A_1^2)

Amplitude Ratio (dB) = 20 x log10 (A_2 / A_1)

Power Ratio	Amplitude Ratio	dB	
100	10	20	
10	3.16	10	
2	1.4	3	
1	1	0	"unity-gain point"
0.5	0.707	-3	"half-power" point
0.1	0.316	-10	
0.01	0.1	-20	

FIGURE 1–2. Power is commonly expressed as a ratio, and this ratio can be expressed in decibels. A decibel is defined as 10 times the log (base 10) of the power ratio. It is therefore equal to 20 times the log of the amplitude (voltage) ratio.



$V_i = I \times R_i$

$V = V_1 + V_2 + V_3$

$R_{eq} = R_1 + R_2 + R_3$

$R_{eq} > R_1$ or R_2 or R_3

$V = I \times R_{eq}$

FIGURE 1–3. Resistors R_1, R_2, and R_3, connected in series, produce a "voltage divider" in which a portion of the input voltage (V_1, V_2, and V_3, respectively) appears across each resistor, and each resistor carries the same current, I. The voltage source sees an equivalent resistance that is equal to the sum of the individual resistances.

The decibel is defined as 10 times the logarithm of the power ratio, or *ratio (dB)* = $10 \times \log (P_2/P_1)$, where P_2 and P_1 are the power values of the variable of interest. Since $P = I \times V$ and $I = V/R$, we can derive that $P = V^2/R$. Thus, power is proportional to the square of the voltage across a load. The dB ratio can also be expressed in terms of voltage (or energy), as *ratio (dB)* = $10 \times \log_2 (V_2/V_1) = 20 \times \log (V_2/V_1)$. Thus, a voltage ratio of 10:1 is equivalent to 20 dB (Fig. 1–2).

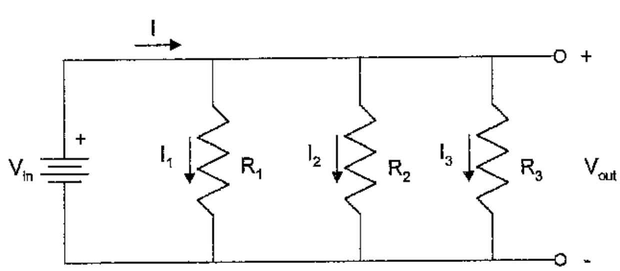
SERIES AND PARALLEL RESISTANCE

Circuits are drawn by connecting the components with wires that are thought of as having zero resistance. Within a circuit, we think of the current as traveling within loops and voltage as existing between points in the circuit. For example, in Figure 1–3, we think of the voltage, V, as producing a current, I, that travels around the single loop. The current then produces voltage drops across the other components. If a component has high resistance (or impedance), a high voltage will be produced across it. If a component has low resistance (or impedance), a low voltage will be produced across it. It is important to understand that the output of most circuits is defined as a particular voltage across a particular pair of points. This pair of points is considered to be the output of the circuit, and the output impedance of the circuit is the impedance between these two points.

In common practice, electrical circuits are encountered in which a number of circuit elements are present such as resistors, capacitors, and electrical potential sources. These circuit configurations appear often, particularly in situations such as the use of electrodes, and their connections to amplifier inputs. Such circuits may then consist of a single current path, or may contain multiple current paths. The most basic of these are series and parallel circuits.

Resistors are said to be in series when they are connected, successively, end to end, so that a current that flows through one of them must then pass through the next, and so on. Figure 1–3 illustrates the situation with series resistances. Since the total current must flow through each of the resistors, each resistor contributes to the voltage built up. This is also called a "voltage divider," because the voltage across each resistor is a fraction of the total. As a result, an equivalent resistance is produced, which is equal to the sum of the resistances. The equivalent resistance is thus greater than any of the individual resistances. We can then calculate the equivalent resistance as $R_{eq} = R_1 + R_2 + R_3$. For example, if $R_1 = 10\text{K}\ \Omega$, $R_2 = 15\text{K}\ \Omega$, and $R_3 = 12\text{K}\ \Omega$, we have: $R_{eq} = 10\text{K} + 15\text{K} + 12\text{K} = 37\text{K}\ \Omega$.

Resistors are said to be in parallel when they are connected together, so that a current can flow through any one of them at a time. Figure 1–4 illustrates what happens with parallel resistances. The current is divided through the resistors, and each carries a share of the total current, resulting in a "current divider." Note that each resistor sees the same voltage, which is the input voltage. As a result, an equivalent resistance is produced that is less than any of the individual resistances. In this case, the net effect is to produce a resistance that is smaller than any one of the individual resistances. Mathematically, we handle parallel resistances by writing: $1/R_{eq} = 1/R_1 + 1/R_2 + 1/R_3$. With R_1, R_2, and R_3 as previously stated, for example, we have: $1/R_{eq} = 1/10\text{K} + 1/15\text{K} + 1/12\text{K} = 0.0001 + 0.000067 + 0.000083 = 0.00025$. $R_{eq} = 1/0.00025 = 4\text{K}\ \Omega$.



$$I_1 = V_{in} / R_1$$

$$I = I_1 + I_2 + I_3$$

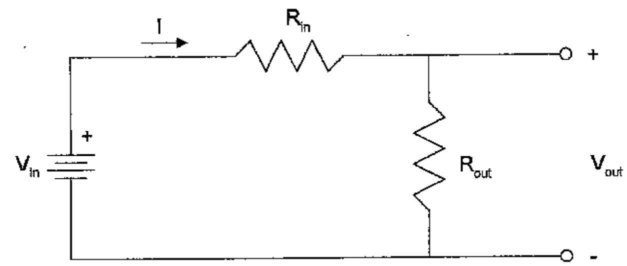
$$1/R_{eq} = 1/R_1 + 1/R_2 + 1/R_3$$

$$R_{eq} = (R_1 \times R_2 \times R_3) / (R_1R_2 + R_1R_3 + R_2R_3)$$

$$R_{eq} < R_1 \text{ or } R_2 \text{ or } R_3$$

$$V = I \times R_{eq}$$

FIGURE 1–4. Resistors R_1, R_2, and R_3, connected in parallel, produce a "current divider" in which a portion of the input current (I_1, I_2, and I_3, respectively) flows through each resistor, but each resistor sees the full input voltage, V. The voltage source sees an equivalent resistance that is less than any of the individual resistances.



$$V_{out} = I \times R_{out}$$

$$I = V_{in} / (R_{in} + R_{out})$$

$$V_{out} = V_{in} \times R_{out} / (R_{in} + R_{out})$$

$$V_{out} < V_{in}$$

$$R_{out} \rightarrow 0 \ : \ V_{out} \rightarrow 0$$

$$R_{out} \rightarrow \text{large} \ : \ V_{out} \rightarrow V_{in}$$

$$R_{in} \rightarrow 0 \ : \ V_{out} \rightarrow V_{in}$$

$$R_{in} \rightarrow \text{large} \ : \ V_{out} \rightarrow 0$$

FIGURE 1–5. A voltage divider produced by a pair of resistors can be viewed as a reducing circuit that produces an output voltage across R_{out} in response to an input voltage, V_{in}, presented through R_{in}. The ratio of the resistors determines the attenuation of the circuit.

When a voltage source is fed into two or more resistors, and the output voltage is taken across a subset of them, a voltage divider results, as shown in Figure 1–5. From the voltage source's point of view, the resistors are in series, so that the voltage is divided between them. However, the output voltage is taken only across R_{out}, so that it sees a smaller voltage. In this case, the smaller R_{out} is, the less voltage will appear at the output. For example, the voltage divider produced by the parallel resistance of an electrode's impedance with the input impedance of an amplifier produces such a voltage drop, which must be minimized, as we shall see later in the chapter.

ALTERNATING CURRENT CIRCUIT CONCEPTS

The previous discussion has described constant, steady electrical current, such as that from a battery through a resistor. Such behavior is called direct current, or DC. Electrical currents often alternate in direction, instead of flowing in one direction. This alternating current, called AC, may occur across a range of frequencies. For example, common household current as provided for residential electrical service operates at 60 cycles or Hertz (Hz); that is, the current alternates from one direction to the other 60 times per second. Physiological signals are often AC in nature. For example, the electroencephalogram (EEG) is typically taken to be an AC signal with a frequency range between about 0.5 and 100 Hz.

AC signals have properties that, in addition to voltage

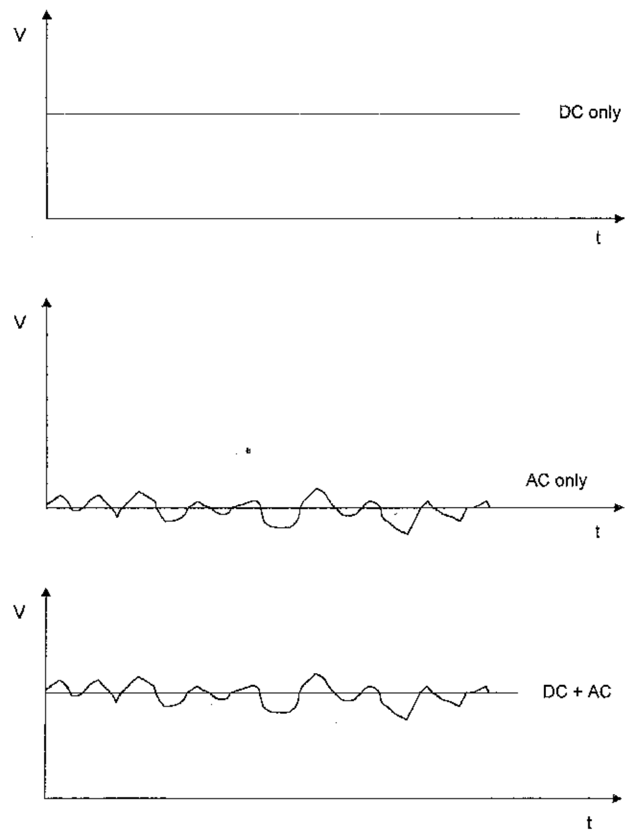


FIGURE 1–6. A signal can generally be thought of as consisting of a DC, or constant bias value, and an AC, or time-varying part. The combination of these two parts produces the entire signal.

and current, must be expressed in terms of frequency. For example, household voltages are generally 110 volts, 60 Hz. If such a voltage is applied to a 50-Ω resistance, the resulting current would be 110/50 = 2.2 amps, also at 60 Hz. AC signals can be graphically displayed as a sinusoidal waveform (Fig. 1–6). Signals that are more complex can generally be described as combinations of sinusoidal components through the technique of Fourier analysis, which is a mathematical formula for breaking any signal into simpler, sine wave components. The effect of any circuit upon a complex signal can generally be understood by considering, separately, its effect with each sinusoidal frequency present in the input, and then combining the individual outputs to get the total output.

If our systems consisted only of resistive elements, circuits would be simple to describe and understand. However, some electrical devices and systems are not purely resistive, because of capacitance. A capacitor is an electrical device or natural system that stores electrical charge, and produces a resulting electrical potential. Capacitance is measured in farads; 1 farad of capacitance produces 1 volt of potential when 1 coulomb of charge is on it. Capacitance is produced whenever a pair of conductors is separated by an insulator, as in a "parallel-plate" capacitor, or in wires that are closely spaced. In common practice, capacitance is measured in microfarads. The current in a capacitor is proportional to its capacitance, and the rate of change of voltage across it, given by I (amperes) = C (farads) × dV/dt (volts/second).

A capacitor can be viewed as having an equivalent resistance, called impedance. A capacitor presents no impedance to high-frequency AC signals, but it presents high impedance to low frequencies. It cannot pass DC signals at all. This is shown in Figure 1–7. The current passing through a capacitor is always associated with the change in the charge distribution across its layers. It is also known as a "displacement" current, because charge must be displaced, for current to flow. DC signals cannot pass across a capacitor indefinitely.

Capacitors have the property that their equivalent resistance, called impedance, is a function of the frequency of the applied voltage. If a DC signal is applied to a capacitor, it will charge up to that voltage and fail to pass more current. Its resistance is thus effectively infinite. We say that a capacitor will not pass DC signals. However, if the applied voltage is AC, the capacitor will allow current to flow, since its alternating nature successively charges and discharges the capacitor.

The equivalent impedance of a capacitor is given by $Zeq = 1/(2 \times \Pi \times f \times C)$, where $\Pi = 3.14159\ldots$, f = the AC frequency in cycles per second, and C = the capacitance in farads. If, for example, a 10-microfarad capacitor is used in a circuit that operates at 60 Hz, the equivalent impedance of the capacitor is $Zeq = 1/(2 \times 3.14159 \times 60 \times 10^{6}) = 265\ \Omega$ (see Fig. 1–7).

The amount of current (and energy) flowing through the capacitor in this case is exactly as it would be if a 265-Ω resistor were used. If, for example, 24 volts AC were applied, the current would be I = 24/265 = 0.090 = 90 milliamps AC current.

Although the impedance of a capacitor is expressed in

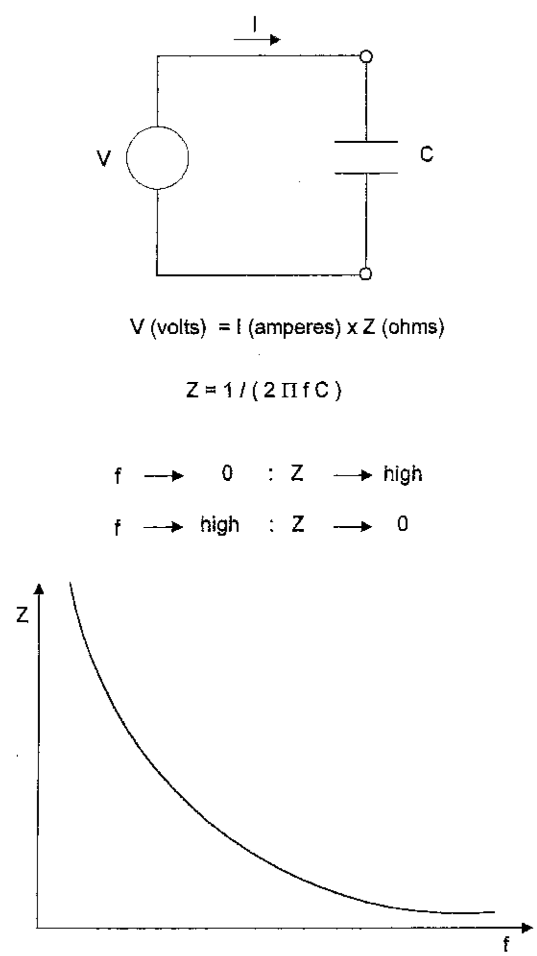


FIGURE 1–7. A capacitor is a circuit element that has an equivalent resistance ("impedance"), Z, that depends on capacitance, C, and frequency, f. The larger the frequency, the smaller the equivalent impedance.

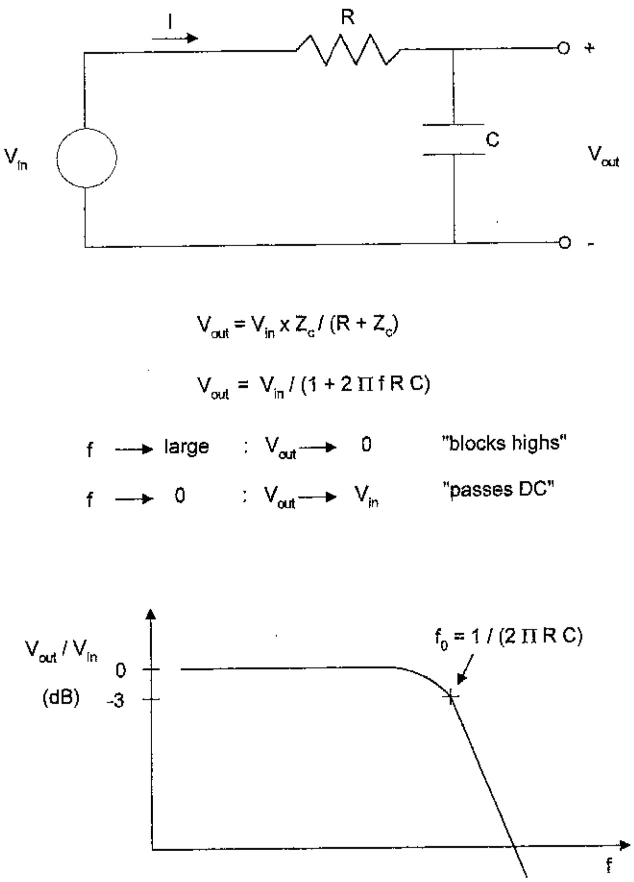


FIGURE 1–8. A "low-pass" filter results when a resistor, *R*, and a capacitor, *C*, are combined as shown in a voltage divider. The output voltage, *V*, produced by current *I* passing through the output capacitor is a function of frequency and is attenuated at high frequencies. Only very low frequencies, or DC voltage, can pass through the circuit.

ohms of resistance to current flow, this is a complex impedance which also introduces so-called phase shifting as well as resistance to current. Its effects are visible in the shapes and sizes of waveforms as they pass through the circuit. Whereas a capacitor freely conducts current at high frequencies, thus presenting a low impedance, an inductor does not conduct current well at high frequencies. Conversely, a capacitor will not pass current at DC (0 Hz), whereas an inductor will. Capacitances and inductances, which can occur by design or may be present as contaminants or "parasitic" elements, will affect the frequency behavior of a circuit, particularly at the high- and low-frequency extremes.

Capacitors can be used in series and parallel, as can resistors. However, the capacitances combine in exactly the opposite manner. That is, capacitors in parallel provide a capacitance that is equal to the sum of the individual capacitances, and capacitors in series provide a capacitance that is less than that of each capacitor alone. Because of this fact, and because the impedance is inversely proportional to the capacitance, the equivalent impedances of series or parallel capacitors behave exactly the same as the equivalent resistances in series or parallel.

LOW-PASS AND HIGH-PASS CIRCUITS

When resistors and capacitors are used together, the combination is known as an RC filter, with either a low-pass or a high-pass configuration. Such circuits have two main properties, their frequency response and their transient response. The frequency response of a low-pass filter is shown in Figure 1–8, and that of a high-pass filter is shown in Figure 1–9. These represent the simplest forms of filters.

Mathematically, for a simple RC circuit, the cutoff frequency is found to be: $f_c = 1/(2 \cdot \Pi \cdot R \cdot C) = 1/(2 \cdot \Pi \cdot \tau)$. For example, if a 10K resistor is used in a low-pass filter with a 0.15-microfarad capacitor, the cutoff frequency is $f_c = 2 \cdot 3.14159 \cdot 10{,}000 \cdot 0.15 \cdot 10^6 = 106.1$ Hz.

Since power is the square of the voltage, at the corner frequency, the voltage ratio is 1 over the square root of 2, or 0.707. In dB, this ratio is: $ratio_{corner} = 10 \cdot \log(0.5) = -3.0$. Thus, the output is "3 dB down" at the corner frequency. This is the point on the graph at which the output, which is at full value for frequencies below this point, is now 3 dB below its full value. This frequency is also sometimes called the "3 dB frequency," as seen in Figures 1–8 and 1–9.

FREQUENCY RESPONSE AND TRANSIENT RESPONSE

The frequency response of an RC circuit can be simply described as the change in the impedance of the capacitor with changing frequency, in the setting of a voltage divider. For example, In the low-pass circuit, with the capacitor's high impedance to low frequencies, the voltage divider trans-

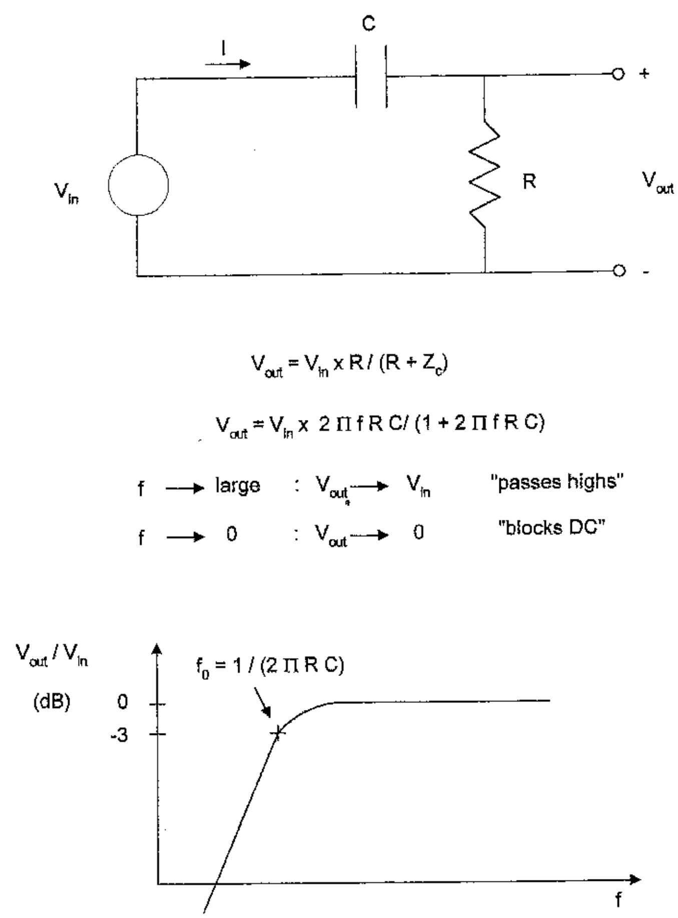


FIGURE 1–9. A "high-pass" filter results when a capacitor, *C*, and a resistor, *R*, are combined as shown in a voltage divider. The output voltage produced by current *I* passing through the output resistor is attenuated at low frequencies and is 0 at DC.

fers most of its input to the output terminals. In effect, the capacitor is more like an "open circuit" and does not reduce the signal. At high frequencies, however, the capacitor conducts readily and presents a low impedance. The output is therefore somewhat "short circuited." Thus, the voltage divider transfers only a fraction of its output to the input; most of the energy is lost across the series resistor. By using this argument and evaluating the actual impedance expression for the capacitor, the exact form of the frequency response can be easily derived. All filter circuits, regardless of their complexity, are understandable in terms of these concepts.

If the output capacitor of a low-pass filter has high capacitance (low impedance), the voltage across it will be low. This is because the capacitor "wants" to conduct current and thus offers low impedance. This may be confusing, since the current flows freely through the capacitor; something that freely conducts current should be associated with a high output. This confusion is resolved by understanding the difference between the series and the parallel impedances encountered in interpreting a circuit. High output is associated with a low series impedance, whereas high output is associated with a high parallel impedance.

A filter is a device whose purpose is to pass specific frequencies while attenuating others. Filters are used to "clean up" signals, for visual suitability or for further processing. Filters generally have low-pass, high-pass, or band-pass characteristics. In addition to the frequency response characteristic, a low-pass or high-pass filter can be understood in terms of its time response, or transient response. These are commonly studied in terms of the step response, which is useful for theoretical, as well as practical, reasons. Instruments often have calibration signals that are essentially step functions,

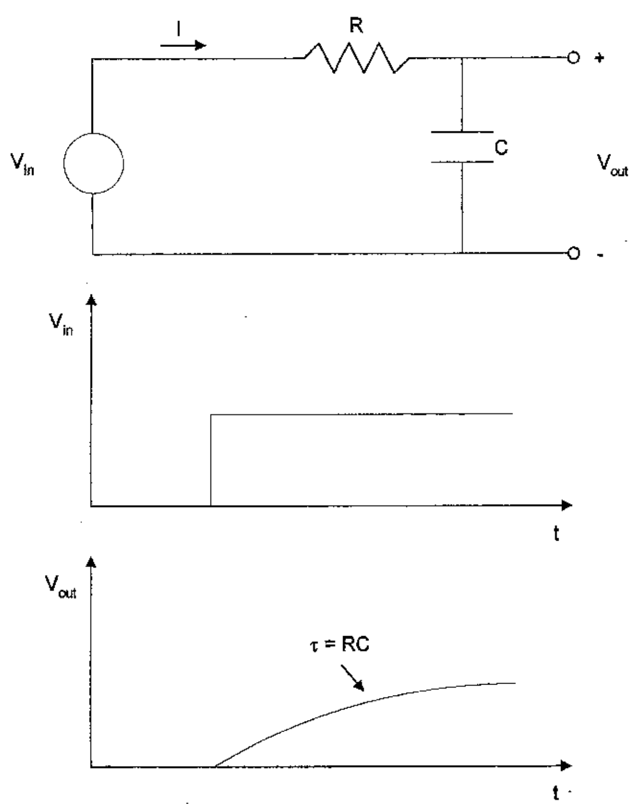


FIGURE 1–10. The low-pass filter has a time-domain response that can be characterized by the "step response." The output will take some time to reach the output value. The response time is characterized by the time constant, τ, which is the product of R and C.

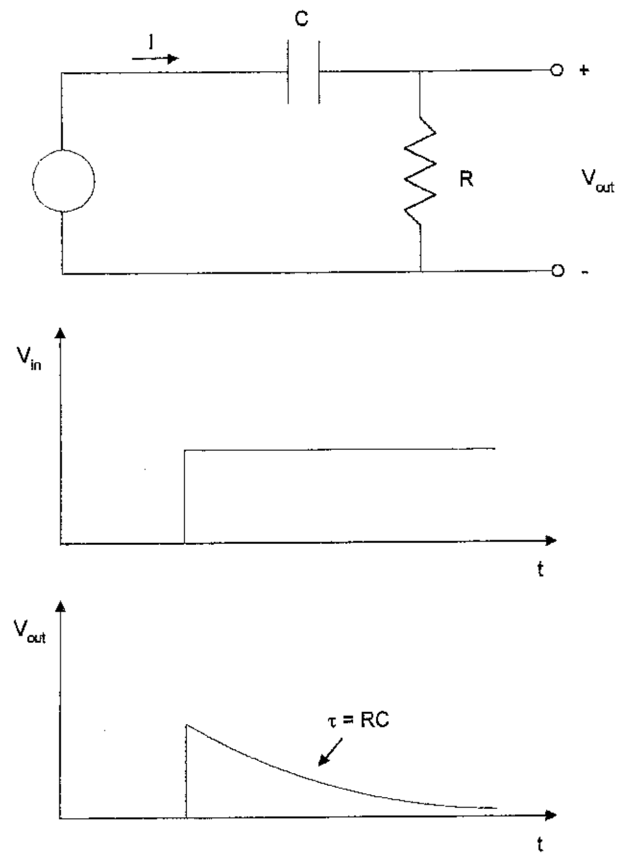
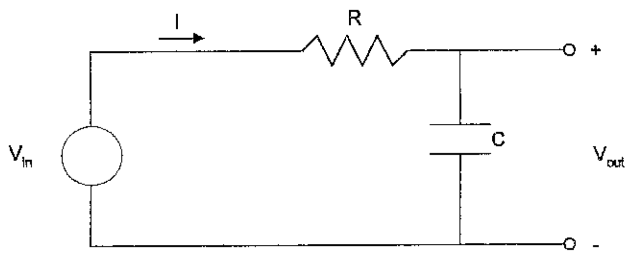


FIGURE 1–11. The high-pass filter has a time-domain response in which the output immediately follows the step input change, then decreases back to zero. The response time is characterized by the time constant, τ, which is the product of R and C.

and the step response is an important way to characterize and calibrate them.

The transient response can be understood from the step response of the circuit, which is the output that occurs if the input voltage is suddenly increased from one level and held at the new level indefinitely. The transient response of a low-pass filter is shown in Figure 1–10. The general form of this response is given as: $V_{output} = V_{input} \times (1 - e^{-t/\tau})$. It can be seen that the output cannot move as quickly as the input, so that it follows with a "lag." However, it is capable of reaching the full output value, given enough time. The transient response of a high-pass filter is shown in Figure 1–11. Although this circuit can immediately produce the full output voltage, it is unable to hold that value, and it will reduce its output to zero, given enough time. This property is sometimes referred to as "droop."

The time response of any low-pass or high-pass filter can be characterized by the "time constant." The time constant of an RC circuit is defined as: τ (seconds) $= R\ (\Omega) \times C$ (farads). If R is in ohms and C is in microfarads, τ is in microseconds. In a simple RC circuit, τ is the time required for the step response to rise from the initial value to 0.63 of the final value when charging or to fall to 0.63 of the initial value when discharging. In each case, the time constant represents the time for the majority of the change to occur. Since the rise or decay of the signal is exponential, the rate of change slows down as time goes by, and the output never actually reaches 100% of its theoretical final, asymptotic value. As another rule of thumb, it takes about three time constants for the output to achieve 95% of its total change.



$f_{co} = 1 / (2 \Pi R C)$

$f_{co} = 1 / (2 \Pi \tau)$

$\tau = RC$

note: $f_{co} = 0.16 / \tau$ (for "single-pole" filter)

f_{co}	τ
1 Hz	0.16 sec
0.5 Hz	0.32 sec
0.16 Hz	1 sec
0.02 Hz	8 sec

FIGURE 1–12. The time constant, τ, is defined as the product of *R* and *C* for an RC circuit. It is related to the cutoff frequency (for simple filters) by a simple proportional relationship.

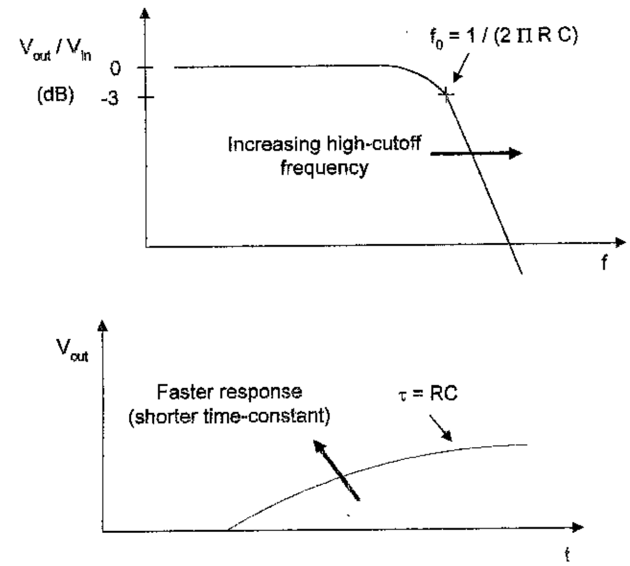


FIGURE 1–13. The relationship between frequency response and time response is shown for a low-pass filter. As the high-cutoff frequency is increased, the time-following response becomes sharper, reflected by a reduction in the time constant.

A "fast transient" is any signal that requires the circuit to respond faster than its time constant will allow it to follow. Such signals are therefore distorted when they pass through the circuit.

For simple filters, there is a direct, inverse relationship between time constant and cutoff frequency. For example, a time constant of 1 second corresponds to a cutoff frequency of 0.16 Hz, and a time constant of 5 seconds corresponds to a cutoff frequency of 0.03 Hz (Fig. 1–12). Filters also have the important property of phase shifting. Because the filter attenuates the signal differently for different frequency components, it introduces a shift in the phase of the output relative to the input. For a low-pass filter, for example (Fig. 1–13), at the cutoff frequency, the output will be shifted 45 degrees relative to the input, and the phase shift will increase with increasing frequency. The situation for a high-pass filter is diagrammed in Figure 1–14. This phase shifting can also lead to phase distortion of the input signal, in which fast transients appear delayed in comparison to slower components, altering the appearance of the signal. In general, phase shifting is not a problem for signals that are far from the cutoffs, but must be considered for signals that are near the limits.

In a clinical example, certain evoked potentials, such as visual and auditory evoked potentials, may have fast components that are near the limits of the recording system. If these components are to be measured with diagnostic accuracy, it is important to ensure that the bandwidth of the recording system is adequate to avoid distorting these waves.

PRINCIPLES OF SIGNAL MEASUREMENT

An amplifier is a device that provides electrical gain, so that its output is generally larger than its input. Amplifiers can provide voltage gain, current gain, or both. Voltage gain is used to increase the value of a voltage, for example, to increase the EEG signal from microvolts to volts. Current gain is used to increase the power of the output, for example to drive a strobe light or a speaker. Amplifiers are active devices, and must have a source of external power in order to develop their output. Amplifiers also have characteristics such as input noise, frequency response, common-mode rejection ratio, and harmonic distortion. These and other properties must be considered in the design, analysis, and application of the various types of amplifiers.

When we talk about voltages, it is useful to define a standard reference voltage for discussion. We say that a voltage of zero volts is ground potential, and any circuit element

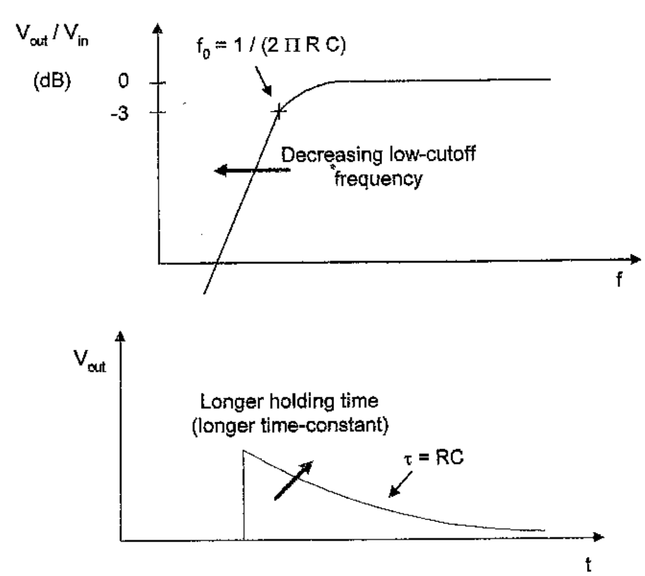


FIGURE 1–14. The relationship between frequency response and time response is shown for a high-pass filter. As the low-cutoff frequency is reduced, the time-following response is able to hold the DC level longer, reflected by an increase in the time constant.

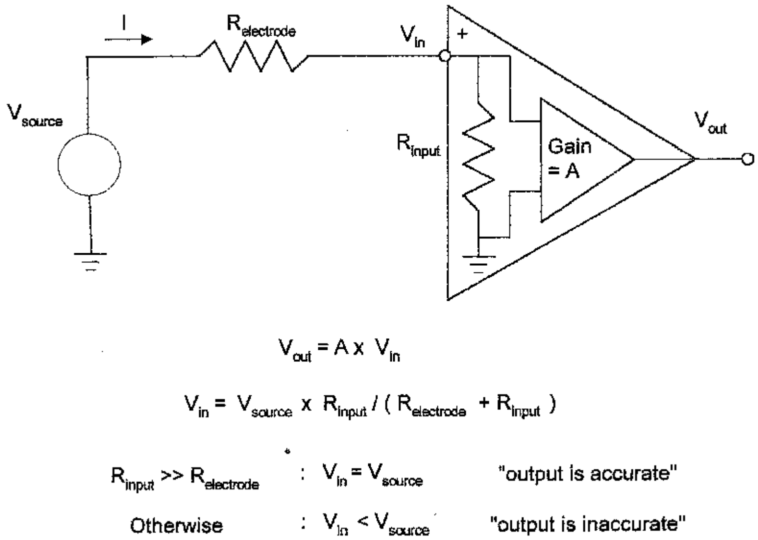


FIGURE 1–15. An amplifier has a characteristic input resistance, R_{in}, that will interact with the resistance of the source, including the electrode $R_{electrode}$. The input current, I, is produced by the input voltage, V_i flowing through both resistances in series. If the amplifier input resistance is much greater than the electrode resistance, then an accurate signal can be recorded. If this is not the case, then the output will not be an accurate reflection of the source voltage; it will also vary with the electrode resistance. The gain of the amplifier is A, so that the output is the product of A and the input voltage, V_{in}.

that is connected to this is said to be grounded. Ground is usually taken to mean literally the potential of the earth, and can be obtained by connecting to one of two things. The first is a cold water pipe, building frame, or other large metal object that is embedded into the earth. While this will usually provide a reliable ground potential, it is not guaranteed. The other, which should be guaranteed, is the ground connection that is to be provided with any three-prong electrical outlet. This plug, which is the extra, round plug in the United States, is connected, according to building and electrical codes, to some large metal object that goes deep into the earth. If this contact does not provide a sound, reliable ground connection, then the plug does not provide adequate safety and is also in violation of governmental ordinances.

Figure 1–15 shows a simple, "monopolar" amplifier. It measures the voltage at its input and produces a proportionally larger output voltage. Such devices are at the heart of all electrophysiological instrumentation. In addition to the obvious property of gain, amplifiers also have the property of having a specific input impedance. The input impedance of an amplifier must be high if it is to accurately measure a voltage from any source. The required magnitude of the input impedance is such that it must be many times larger than the source impedance of the measured entity.

DIFFERENTIAL AMPLIFIERS AND THE EFFECTS OF INTERFERENCE

In clinical electrophysiology, differential amplifiers (Fig. 1–16) are commonly used. These provide an output that is proportional to the difference between two inputs. This is useful because typical electrophysiological sources have, in addition to the (usually small) differential voltage that is desired to be measured, a potentially large common-mode voltage that appears at both inputs. Common-mode voltages include electrical interference, effects of breathing, electrocardiogram (ECG), and so on, but nonetheless appear on the input leads. In order for a differential amplifier to provide an accurate signal, it must have the ability to cancel out common-mode signals. This property is known as the "common-mode rejection ratio," or CMRR. For effective clinical recording, this must be very high (>100 dB) on typical electrophysiological instruments.

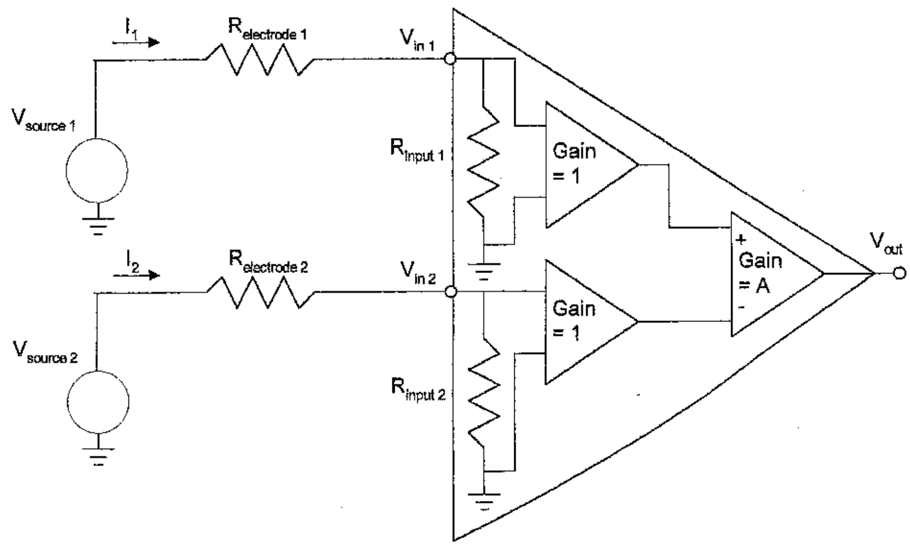
Figure 1–16 shows that the CMRR of an electrophysiological amplifier is also dependent on the relative magnitudes of the source (including electrode) resistances compared to the amplifier input resistance. The amplifiers must have a very large input resistance or else the effects of any electrode impedance mismatch will be to degrade the CMRR, allowing (especially 60-Hz) common-mode signals to appear at the output, thus providing a noisy signal. The amplifier operates by amplifying only the difference between the inputs, and not their absolute values. In order to do so, it must effectively subtract the two common-mode inputs. The accuracy with which the amplifier can do this is what is specified by the CMRR.

Note that 60-Hz electrical interference, as caused by electromagnetic induction in the wiring, appears first as an induced current, then causes voltages to appear by virtue of the resistances and impedances in the circuits. Thus, high resistances in critical paths, such as electrode connections, cause susceptibility to interference and should be avoided. Voltage introduced in the leads in this way is often common mode, so that a high CMRR will help to minimize the effects of 60-cycle noise in the environment.

Another source of unexpected circuit components is the existence of stray or parasitic elements. For example, there may be parasitic capacitance in the electrode wires leading from a patient, and there may be parasitic inductance in these wires as well. Although connecting wires ideally have no resistance, inductance, or capacitance, real-world devices are never ideal. Although stray or parasitic values are generally small, they cannot be entirely neglected. They generally appear when the extreme limits of performance are encountered, such as noise, frequency response, or electrical interference. For example, the presence of stray capacitance in the electrodes or wires will cause problems for high-frequency recording, as these signals may be attenuated by stray RC circuits that appear in the system. Often, these situations are dealt with by using superior materials, special insulation, or shielding, or by using specially designed components or instruments.

APPLICATION TO ELECTROPHYSIOLOGY

Figure 1–17 is a simple circuit model of phenomena that occur when a low-level electrophysiological potential, such



$$V_{out} = A \times (V_{in\,1} - V_{in\,2})$$

$$V_{in\,i} = V_{source\,i} * R_{input\,i} \,/\, (R_{electrode\,i} + R_{input\,i})$$

If $V_{source\,1} = V_{source\,2}$ (common-mode signal):

$R_{input\,i} >> R_{electrode\,i}$	: $V_{out} = 0$	"good common-mode rejection"
Otherwise	: $V_{out} \neq 0$	"poor common-mode rejection"

FIGURE 1–16. A differential amplifier, such as used in electrophysiology, has two inputs, and its output is the difference between them. There are two voltage sources, $V_{source1}$ and $V_{source2}$, producing two input currents, I_1 and I_2. Thus, two electrodes must be used with resistance, $R_{electrode1}$ and $R_{electrode2}$, plus each input has its own input resistance, R_{input1} and R_{input2}. If the input resistances are much larger than the electrode resistances, then the inputs will be matched, and the amplifier will be able to cancel out any common-mode signal that appears on both inputs. However, if this is not the case, than any electrode resistance mismatch that exists will produce an input difference between the channels, and appear as an error signal on the output.

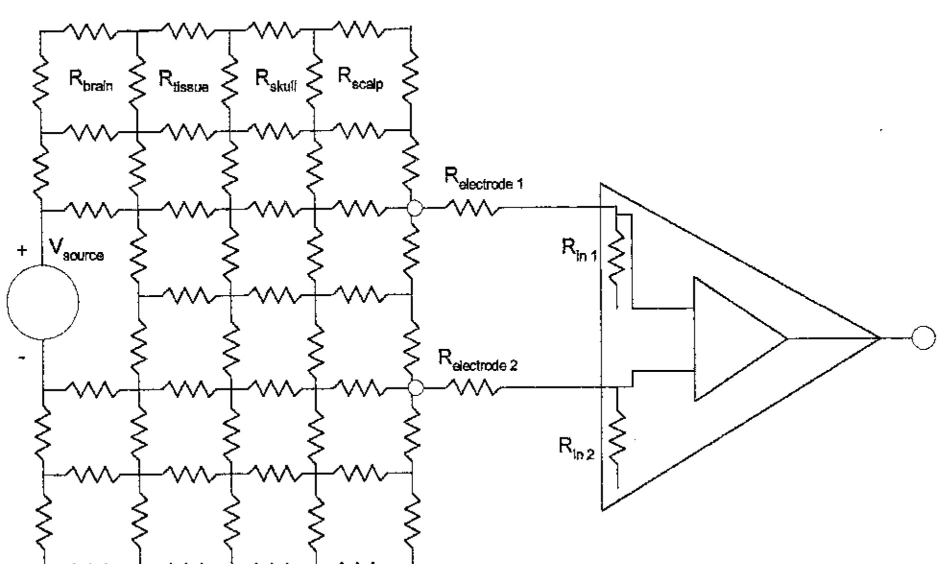


FIGURE 1–17. A biological source, such as the EEG, can be modeled as a voltage source that passes current through a distributed network of resistances (a "volume conductor"), representing the layers of brain (R_{brain}), tissue (R_{tissue}), skull (R_{skull}), and scalp (R_{scalp}). The electrodes pick up the resultant signal on the surface and connect it to an amplifier, through electrode resistances $R_{electrode1}$ and $R_{electrode2}$, across which it is carried to the input resistances R_{in1} and R_{in2}, where it can be measured.

as the electrical field of a brain cell, is measured using electrodes and a sensitive amplifier. The associated events are as follows:

1. Physiological processes displace ions.
2. Local potentials are produced.
3. Currents are conducted throughout the head.
4. Potentials appear on the scalp and the electrodes.
5. Tiny currents are induced in the wires.
6. Potentials appear at the amplifier inputs.
7. Larger potentials appear at the amplifier outputs.
8. Something visible occurs such as pen deflection, meter indication, oscillograph display, computer sample, and so forth.

These basic events, with minor modification, explain how any electrophysiological phenomenon can give rise to its measurable counterpart, for example, muscle activity producing the electromyogram (EMG), eye activity producing the electrooculogram (EOG), or retinal activity producing the electroretinogram (ERG).

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