Technical Aspects of Sleep Testing

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Objectives:

- Understand basic electrical concepts relevant to polysomnography
- Learn the basic operation of amplifiers
- Appreciate the function and operation of filters
- Understand aspects unique to digital polysomnography

Key words: amplifiers; artifacts; electrical concepts; filters; polysomnography

Polysomnography studies are an essential tool for the sleep physician and aid in the diagnosis and treatment of sleep disorders. The term *polysomnography*[1,2] refers to the recording, analysis, and interpretation of multiple physiologic signals collected simultaneously. Typical physiologic signals that are collected as part of the polysomnography study include, but are not limited to, EEG, electromyogram, electrooculograph, ECG, and respiratory signals. Rapid advancements in technology have transformed the field since analog studies were collected on paper to the present, computer-assisted collection of digitally transformed studies. Sleep physicians must therefore have an understanding of a broad array of principles underlying the collection of the various signals. In this chapter, we will review basic electrical concepts, the operation of differential amplifiers, the use of filters and filtering, unique aspects of digital polysomnography, and common artifacts encountered during recordings.

Electrical Concepts

The physiologic signals collected during the course of polysomnography are representations of bioelectrical potentials (*ie*, electrical activity) from different sources within the human body. It is worthwhile to take a moment to discuss the electrical concepts that govern the movement of current and the properties that affect it. An understanding of these concepts will help in understanding the function of amplifiers.

Current, Voltage, and Resistance

Electrical current (measured in amperes) refers to the movement of charged particles through conductive material.[3] Particles of similar charge will distribute uniformly within a conductive material, but will not result in the net movement of the charged particles through the material; therefore, no current is produced. An electrical current is produced when a net movement of charge occurs across the conductive material. Electrical current can be direct or alternating. The term *direct current* (DC) refers to the net movement of charged particles within a circuit in one direction. The term *alternating current* (AC) refers to an oscillatory current that changes polarity and direction periodically. The number of oscillations or cycles per second is referred to as the *frequency* (measured in hertz).

The net movement of charge is generally induced by an object, such as a battery, that can generate an *electromotive force*. The electromotive force is quantified as the potential difference in charge between two terminals within an electromotive force device and is represented as *voltage* (measured in volts).

All materials have a property called *resistance* (R; measured in ohms), which restricts the flow of current through the material. Resistance is inversely related to conductance. The mathematical relationships among current, voltage, and resistance are provided by Ohm's law:

$$V = I \times R$$

Capacitance, Inductance, and Impedance

Ohm's law, as stated above, can be directly applied to DC circuits. In AC circuits, however, the concept of resistance is more complicated and requires an understanding of two additional electrical concepts, capacitance and inductance. A capacitor is an electrical device within a circuit that stores energy between two plates and resists changes in voltage. Capacitors are useful in the design of low-frequency and high-frequency filters. *Capacitance* (C; measured in farads) is a measure of the charge stored for a given voltage. The application of an AC current to a capacitor results in the development of resistance to the current, which is referred to as *capacitive reactance* (X_C).

Inductors are another electrical component that are used in circuits and are formed by coils of conductive material (*eg*, copper wire) around a core of ferromagnetic material (*eg*, iron). Energy is stored within the inductor as an electromagnetic field, which opposes a change in current. Inductors are also useful in the design of electrical filters. *Inductance* (L; measured in henries) is the amount of voltage generated per change in the current rate of 1 A. The resistance to an AC by an inductor is referred to as *inductive reactance* (X_L). Resistance within an AC circuit, referred to as *impedance* (Z; measured in ohms), is calculated from the resistance of the circuit, the capacitive reactance, and the inductive reactance. Once determined, impedance can replace resistance in Ohm's law for the analyses of AC circuits and would take the following form:

$$V = I \times Z$$

Knowledge of impedance has important applications in polysomnography. Specifically, low impedance will result in a high-quality physiologic signal through improvements in the signal/noise ratio. Conversely, high impedance will result in a low-quality signal through reductions in the signal/noise ratio. Impedances < 5 KΩ are ideal for optimizing the collection of AC signals.

Differential Amplifiers

Amplifiers are used in polysomnography recordings for differential discrimination and amplification.[4] The term *differential discrimination* refers to the ability of the amplifier to reveal differences in potentials between two inputs and to reject potentials that are common to the two inputs. The term *amplification* refers to the ability of the amplifier to increase the size of the potential differences and to drive the analog-to-digital converters.

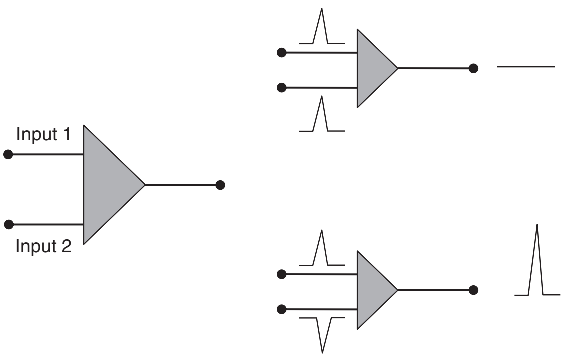

Figure 1. Basic operation of differential amplifiers. Two inputs come into an amplifier, with one signal output after signal conditioning. If the two inputs into the amplifier are of the same polarity and amplitude, the output signal from the amplifier will be zero (common mode rejection of the potentials; *top*). If the two inputs into the amplifier are of different polarities, but the same amplitude, the output signal from the amplifier will be twice the amplitude of the input signals (amplification of different potentials; *bottom*).

The purpose of differential discrimination is to minimize the electrical interference from other electrical sources within the body, the environment within which the recording is collected, and other equipment in the local environment. This is performed by relating two inputs into the amplifier to each other, which results in a single output voltage that is then displayed (Fig 1).

The *polarity* (*ie*, direction of displayed deflection) of the output signal is dependent on (1) the polarity of the two inputs into the amplifier, and (2) the input terminal to which the signal is applied (input 1 vs input 2).[4] In other words, when two electrical signals are sent to an amplifier, greater negativity at input 1 with respect to input 2 results in an upward deflection. In contrast, greater negativity at input 2 relative to input 1 results in a downward deflection. By convention, potentials with negative polarity are presented as an upward deflection, whereas potentials with a positive polarity are presented as a downward deflection. If the two inputs into the amplifier are of similar polarity and amplitude, the output signal from the amplifier will zero (*ie*, rejection of the potentials) [Fig 1, *top*]. If the two inputs into the amplifier are of different polarities but the same amplitude, the output signal from the amplifier will be twice the amplitude of the input signals (*ie*, amplification of different potentials) [Fig 1, *bottom*]. The examples above represent the simplest representation of the amplifier output. With experience, it becomes more evident that a particular signal output can be the result of an infinite number of input signals with differences in polarity, amplitude, and timing.

Biopotentials are not equally distributed over the source of interest (*eg*, the brain); however, electrical interference typically affects all areas over the source of interest. The purpose of differential amplification is to eliminate the electrical interference at the inputs in order to detect the biopotentials of interest that are localized to the area of interest. The ability to discriminate between like potentials and differing potentials is also referred to as *common mode rejection*. This ability is quantified as the *common mode rejection ratio* and is the ratio of the common mode input voltage and the output voltage. The higher the ratio, the greater the ability of the amplifier to reject the common voltages at the two inputs. Most high-quality polysomnography systems have a common mode rejection ratio of 10,000:1. Although the ability of the amplifier to reject common voltages is greater in devices with high ratios, this does not always guarantee the elimination of common voltages and could make distinguishing biopotentials from electrical interference difficult. Failure of the amplifier to discriminate is typically due to either a loss of an effective ground connection or unequal impedances between the two inputs.[4] A loose connection from a ground electrode or an input electrode can result in electrical interference that is difficult to distinguish from the true biopotentials at the input electrode. Unequal impedance between electrodes typically occurs when there is a loss of contact. As a result of unequal impedance, biopotentials of equal amplitude at the scalp will appear with different amplitudes at the amplifier input. As a result, the remaining secured electrode input is referenced to the ground electrode. A common result of unequal impedance is the appearance of a 60-Hz artifact. The absence of a ground or presence of an ineffective ground results in the inputs "floating" without reference to the potential level at which the amplifier references input 1 to input 2.[5]

Differential amplifiers amplify the difference in voltage between the input signals in order to drive an analog-to-digital converter. This amplification factor is also called *gain*. For example, if an amplifier is set to provide an output voltage of 1 V for a 1-mV input, the gain would be 1,000. Gain is sometimes expressed in decibels (dB; where 1 dB = 20 × log(gain); in our example, this would be 60 dB). Amplifier *sensitivity* refers to the ratio of the input voltage to the vertical size of the waveform produced and is often expressed in microvolts per millimeter. As sensitivity increases, the vertical size of the waveform decreases. As sensitivity decreases, the vertical size of the waveform increases.

Amplifiers that are used in polysomnography equipment include both AC and DC amplifiers. AC amplifiers can amplify only AC signals, whereas DC amplifiers can amplify both AC and DC signals.[3]

AC amplifiers are typically used to record high-frequency signals such as EEG and electromyogram. AC amplifiers have controls to set the sensitivity, polarity, and filters in order to condition the signal. Low filters and high filters are available to isolate the bandwidth and biopotentials of interest (see "Filters and Filtering"). A notch filter is often provided to assist in the elimination of a 60-Hz artifact if needed. DC amplifiers generally have a setting to alter the reference baseline of the signal recorded and have adjustments for sensitivity and filtering as well. Due to the use of DC amplifiers for recording low-frequency signals (*eg*, respiration, pressure, oximetry, and respiratory effort), a low-frequency filter is not included, although a high-frequency filter is present.

Patient Ground, Electrical Ground, and Electrical Safety

It is important to distinguish between the patient ground and the electrical ground when considering the issue of electrical safety for the patient and the technologist in the sleep laboratory. The purpose of the patient ground is only to reduce the presence of electrical interference and to improve common mode rejection. It does nothing to protect the patient or the technologist. Common locations for the patient ground are located on the head, typically at the Fpz point, based on the 10–20 system. This is because the Fpz point generally lacks true biopotential sources from the brain and can aid in the detection of unequal impedance due to the proximity of the leads to the eyes.[5]

Electrical injury can occur only if an individual is connected to an electrical apparatus. Injuries can include burns, seizures, arrhythmias, and permanent damage to nervous system tissue. Dry, intact skin has high impedance, which can protect patients from current flow. Wet skin, wounds, or pacemaker wires have low impedance and can make the patient susceptible to electrical injury with current flow. A 0.5- to 1-mA current at 60 Hz is near the threshold of pain perception. A current of 100 to 300 mA (*ie*, a macroshock) at 60 Hz is enough to induce fibrillation.[6] In order for current to flow, this requires a source of the current and a complete circuit.[4,6] A circuit is designed so that the patient does not form a complete circuit through which excessive current can flow and cause injury. The power unit for the polysomnography equipment represents one source. If there is a short circuit within the electrical power source, the fault current flows to the chassis. If the patient or technologist is touching a conductor and the ground is disabled, excessive current will be received by the individual, and electrical injury could occur. To prevent electrical injury, the polysomnography equipment has an electrical ground at the source of power. One of the prongs represents a low-resistance circuit and allows the earth to act as a sink in case of a short circuit.

Filters and Filtering

Filters are used to exclude high and low frequencies so that biopotentials in the range of interest are more clearly recorded without distortion. Low-frequency filters (also known as *high-pass filters*) are used to attenuate the amplitude of slow-frequency waveforms. High-frequency filters (also called *low-pass filters*) are used to attenuate the amplitude of high-frequency waveforms. Notch filters are used to eliminate frequencies due to electrical interference, typically centered at 60 Hz. The most important concept to bear in mind is that filters are not absolute in their elimination of particular frequencies. Filters provide a continuum of gradual filtering both below and above the specified frequency cutoff. Table 1 provides a list of commonly recommended filter settings from the published American Academy of Sleep Medicine *Manual for the Scoring of Sleep and Associated Events*.[7]

Low-Frequency Filters

Low-frequency filters are designed to attenuate slow-wave frequency waveforms that are not of physiologic interest, such as galvanic skin responses, DC electrode imbalance, and respiratory artifact.[1,4,8] The setting of a low-frequency filter specifies the cutoff frequency at which the amplitude of that frequency is reduced by a set percentage, which is typically 20 to 30%, depending on the system used. Regardless of the cutoff frequency that is selected, that particular frequency will be attenuated by 20 to 30%. The attenuation of frequencies below the cutoff frequency becomes more severe as the frequency

Table 1. *Recommended Sampling Rates and Filter Settings**

	Sampling Rates, Hz			
Signal	**Desirable**	**Minimal**	**Low-Frequency Filter, Hz**	**High-Frequency Filter, Hz**
EEG	500	200	0.3	35
EOG	500	200	0.3	35
EMG	500	200	10.0	100
ECG	500	200	0.3	70
Airflow	100	25	0.1	15
Oximetry	25	10		
Nasal pressure	100	25		
Esophageal pressure	100	25		
Body position	1	1		
Snoring sounds	500	200	10.0	100
Rib cage and abdominal movements	100	25		

*Maximum electrode impedance, 5 kohms; minimal digital resolution of amplifiers, 12 bits per sample. Additional specifications are available in Iber et al.[7]

becomes progressively slower; this is also known as *roll-off*.

Another important concept in filtering is the fall time constant (typically referred to as the *time constant*). The time constant is the time required for a square-wave voltage applied to an amplifier to decay to 63% of its peak amplitude and describes the effects of a low-frequency filter on the square-wave pulse.[4] In electrical terms, the time constant is equal to the resistance × the capacitance (TC = R × C). The low-frequency filter setting and the time constant are inversely related. The higher the low-frequency filter, the shorter the time constant. The lower the low-frequency filter, the longer the time constant. By setting a time constant for an amplifier at a longer time, slower frequency waveforms are amplified without significant filtering. In older analog systems, knowledge of the time constant was important because certain amplifiers did not have a low-frequency filter and only had the ability to set the time constant.

High-Frequency Filters

High-frequency filters are designed to attenuate fast-frequency waveforms. The setting of a high-frequency filter is similar to that for a low-frequency filter, whereby a cutoff frequency is specified, above which the amplitude of that frequency is reduced.[4] In contrast to low-frequency filters, many digital systems will have a steeper roll-off for the high-frequency filters. This allows analog filtering prior to digitization and reduces demand on the sampling rate of the analog-to-digital converter.

Notch Filters

Notch filters are designed to eliminate electrical interference generated by other devices using AC.[3,4] In the United States, this is typically at 60 Hz, whereas in other countries the frequency of AC current may be 50 Hz. Notch filters severely attenuate (*ie*, high roll-off) frequencies centered at 60 Hz but may not completely filter them out. Notch filters should not be used routinely, because the presence of a 60-Hz artifact can represent a useful warning sign to the astute technologist. The appearance of a 60-Hz artifact should warn the technologist of the possibility of unequal impedance between electrodes (*eg*, loss of electrode contact or sweating) or incorrect input selection. The technologist would be better served to correct the cause of the problem rather than to use the notch filter. The notch filter should be used only after this troubleshooting has occurred because application of the filter can obscure relevant physiologic electrical phenomenon such as spike activity.

Aspects Unique to Digital Polysomnography

Rapid advancements in technology have led to the computer-assisted collection of polysomnography recordings. The term *digital polysomnography* refers to the collection, digitization, and display of data.[4,9] The advantages of digital polysomnography include flexibility in the time scale display of recorded data, autocorrection of amplifier gains, self-diagnostic tests of amplifier functions, software-controlled in-line impedance testing, easy storage of data, the ability to move between different points of time within a recording, and the application of various digital filters while keeping the original digitized signal, to name a few.[1,6] The disadvantages of digital polysomnography include a lower display resolution than that for paper, signal distortion due to aliasing, the need for a more attentive technologist, and computer-related problems. There are several features unique to the digitization of data compared with analog collection and display of the data that the technologist and sleep physician should be cognizant of. In particular, the conversion of an analog signal to a digital signal is dependent on several key components, including the sampling rate, the number of bits of resolution available, and the input voltage range.

Sampling Rate and Aliasing

The term *sampling rate* is the frequency at which an analog signal is converted to a digital signal.[4] Table 1 provides a list of commonly recommended sampling rates by signal type.[7] For example, a sampling rate of 100 Hz implies that the analog signal has been sampled every 0.01 s, resulting in the digitized signal's having 100 samples per second of the analog signal. To adequately represent an analog signal in a digitized form, it must be appropriately sampled. According to the Shannon's sampling theorem (also known as the *Nyquist theorem*), a signal can be digitized and restored to accurately represent the frequency of the analog signal if sampled at twice the highest frequency (known as the *Nyquist rate*) contained within the signal. For a digital signal to reproduce the quality of an analog signal would require a sampling rate at least six times faster than the fastest frequency to be visualized. If a signal is sampled below the Nyquist rate, aliasing can occur.

The term *aliasing* refers to the misrepresentation of a signal as a slower frequency waveform. For example, if a 100-Hz signal is sampled at 100 Hz, only one data point per second at the same amplitude would be represented after the analog-to-digital conversion process. Each point would be connected by a line and would be interpreted to represent a 0-Hz signal. As the sampling rate is increased >100 Hz, a digital waveform slower than 100 Hz is created (which is still a false representation of the frequency of the original signal) until a sampling rate of ≥200 Hz is achieved. Aliasing can be avoided by either of the following: (1) increasing the sampling rate; or (2) filtering the analog signal prior to digitization to remove activity with a faster frequency than half of the analog-to-digital converter sampling rate.[9] Aliasing is difficult to recognize when it occurs; therefore, appropriate sampling and filtering are important safeguards in the digital collection of polysomnography data.

Bit Resolution and Input Voltage

The vertical resolution of a signal is dependent on the number of binary bits used to represent the digital values.[4] The number of bits used to represent a sampled analog signal is known as the *resolution of the analog-to-digital converter*. The amplitude of a signal is assigned to discrete, nonoverlapping amplitude levels that are defined by the number of bits available in the digital recording equipment. For example, if a system has 12 bits, this would represent 212 or 4,096 levels (±2,048 levels) for the voltage range of the signal to be represented. Because most amplifiers allow an input voltage range of ±5 V, this would mean that each level could discriminate between a data point of not <2.4 mV (10 V per 4,096 levels). In other words, changes in voltages <2.4 mV would not be reflected as a change in amplitude. Changes in voltage >2.4 V would be reflected as a change in amplitude and would be reflected as a smoother signal that represented a higher fidelity reproduction of the analog signal.

For polysomnographic recording systems, a bit resolution of 10 to 12 bits is desirable. Fewer bits would result in large voltage changes being undetected and small voltage changes being overrepresented.

Monitor Aliasing

It is also important to be aware of the potential for monitor aliasing. The term *monitor aliasing* refers to aliasing of a signal that occurs due to limitations of the monitor display. A digital representation of a signal over a 30-s epoch rarely has the fidelity of the same signal over the same epoch seen with paper recordings, due to the limitations of pixel resolutions on computer screens. A minimum computer monitor resolution of 1,600 × 1,200 pixels is recommended. A 30-s epoch represented over the horizontal span of 1,600 pixels would result in an effective sampling rate of 53 Hz. As a result, the displayed signal may appear distorted. As the time scale is decreased to small epochs, the resolution of the signal will improve. Nevertheless, the display of a digital system rarely rivals that seen in the traditional paper recording.

Artifacts

Despite careful attention to the preparation of the patient and the recording equipment, the presence of high-quality differential amplifiers with high common mode rejection ratios, and extraneous electrical activity can appear in a recording and are called *artifacts*.[6,10] The recognition and correction of artifacts are central to the duties of the recording technologist and the supervising sleep physician. A complete discussion of all artifacts that one can encounter is beyond the scope of this chapter; however, a summary of common artifacts, their source, and approaches to troubleshooting is presented in Table 2.

Troubleshooting of any artifact begins with the patient and the recording. The technologist should

Table 2. *Common Artifacts Encountered in a Polysomnography Study*

Artifacts	Artifact Appearance	Cause of Artifact	Strategies To Address Artifact
Muscle artifact	High-frequency artifact typically seen in EEG and EOG channels; difficult to distinguish from activity in β frequency range	Increased muscle tension	Will generally resolve with sleep onset due to muscle relaxation
Movement artifact	Sudden, brief bursts of high amplitude, high frequency; can also appear as slow-frequency movements when isolated to the head	Spurious static potentials caused by body movement; slower movements may be due to slight movement of electrodes on scalp or swaying of wires (*eg*, head movement)	No intervention; position wires away from contact with the head or body
Sweat artifact	Slow-frequency waveforms seen in EEG and EOG channels can appear asymmetric	Changes in salt content of sweat can alter the ionic composition of the conducting gel	
Pulse artifact	Small-amplitude, low-frequency waveform that corresponds to the pulse rate	Pulsations of nearby artery resulting in electrode movement	Repositioning of electrode
ECG artifact	Appearance of QRS-like waveform corresponding with the ECG signal	Detection of electrical current from the myocardium	Reposition the ECG electrodes higher up on the chest or to the upper back, close to the shoulders; repositioning of the reference leads (*ie*, M1 or M2); use of a jumper cable between M1 and M2 to increase common signal within the head electrodes to increase likelihood of common mode rejection
Respiratory artifact	Slow-frequency waveform seen in high-frequency channels that corresponds to the frequency of respiration	Most often due to an electrode wire in contact with the chest and abdomen	Reposition affected electrode wires
60-Hz artifact	Moderate frequency, highly regular	Poor electrode contact; defective lead wires; inadequate grounding; nearby electrical equipment	Reapplication or replacement of electrode; reapplication or replacement of the ground; turn off unnecessary electrical equipment; increased shielding
Electrode popping	Abrupt vertical transients, typically of positive polarity confined to single electrode	Due to abrupt changes in impedance	Reapply electrode more firmly; reapplication of conducting gel to improve conductance; replace lead
Reversed polarity	Change in polarity of waveform	Accidental inverting of waveform; movement of sensor (*eg*, migration of an abdominal effort gauge more superiorly)	Adjust sensor if possible; review biocalibrations to determine if inverting of signal was accidental

follow the signal path from the patient to the recording device.[1] Often, an artifact can be localized to a set of leads. In this situation, the technologist should identify the leads in which the artifact is seen in order to identify the common lead and localize the source of the artifact. When artifacts are more generalized, this may reflect a poor patient ground electrode or a loose equipment connection. Artifacts due to amplifier problems are more unusual.

Summary

The conduct of polysomnography studies requires an understanding of basic electrical concepts, differential amplifiers, filtering, and analog-to-digital conversion. An understanding of these concepts will assist the sleep physician in the interpretation of polysomnography studies and place the results in the context of the patient history.

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