Principles and Practice of Clinical Electrophysiology of Vision

Editors

John R. Heckenlively, M.D.
Professor of Ophthalmology
Jules Stein Eye Institute
Los Angeles, California

Geoffrey B. Arden, M.D., Ph.D.
Professor of Ophthalmology and
Neurophysiology
Institute of Ophthalmology
Moorfields Eye Hospital
London, England

Associate Editors

Emiko Adachi-Usami, M.D.
Professor of Ophthalmology
Chiba University School of Medicine
Chiba, Japan

G.F.A. Harding, Ph.D.
Professor of Neurosciences
Department of Vision Sciences
Aston University
Birmingham, England

Sven Erik Nilsson, M.D., Ph.D.
Professor of Ophthalmology
University of Linköping
Linköping, Sweden

Richard G. Weleber, M.D.
Professor of Ophthalmology
University of Oregon Health Science Center
Portland, Oregon

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Amplifiers and Special-Purpose Data Acquisition Systems

J. Vernon Odom

Numerous sources offer practical assistance in understanding and choosing amplifiers and special-purpose systems. Some of the most practical are informational pamphlets by manufacturers. Other sources include general texts on electronics,[1] signal processing,[2, 5] and electroencephalography (ERR),[8, 9] and other guides.[6, 7]

AMPLIFIERS

The electrical potentials elicited by visual stimulation are too small to drive most recorders or to be accurately detected by the analog-to-digital converters (ADCs) that form the initial stage of most commercial systems for processing physiological signals. Therefore, a system of preamplifiers and amplifiers is required to increase the voltage of the signal. In the following sections, amplifiers and their characteristics will be described.

In discussing amplifiers it is also necessary to consider the characteristics of the signals they will amplify and the noise that must be minimized or eliminated by them. Ideally the signals to be amplified would be only those generated by neural activity of interest, and *all* other electrical features would be filtered out. To amplify the signals of interest and filter the unwanted signals, it is helpful to consider the visual signals and the major sources of physiological and electrical noise. Table 24–1 gives the major biological signals elicited by visual stimulation, their frequency range, their amplitude range, and the gain or amplification required to have an output peak-to-peak voltage of 1 V. Also listed are the characteristics of other biological signals that may be noise relative to visual signals, such as the electroencephalogram and electromyogram. *Naturally, these* values can only be approximate. Table 24–2 presents common sources of electrical interference, their origins, and methods to minimize them.

Preamplifiers

Generally, the subject's electrodes are connected to a preamplifier. The purpose of the preamplifier is to provide initial amplification (10× to 1,000×) so that as the signal is transmitted along cables to the final amplification stage, the effects of long cables can be minimized. Frequently preamplifiers provide minimal filtering.

An essential concern is the patient's safety. While attached to the electrophysiological equipment, the patient is potentially part of a 110- to 220-V circuit. The several pieces of equipment in that circuit may or may not share the same ground. Many large buildings such as hospitals have several grounding circuits. In the unlikely event of major electrical failure of the recording equipment, the main's electricity could pass through the patient, and a ground fault could prove fatal. Consequently, the patient should be protected from the improbable event of such a major accident by electrical isolation from the equipment during the entire test.

The most frequent means of doing this is to use an isolation preamplifier. Isolation amplifiers isolate the power supply of the amplifier from the power supply of the input stage or from the power supply of both the input and output stages. One must en-

TABLE 24–1.
Visual Signals and Physiological Noise

Signal	Frequency Range (Hz)	Amplitude Range (Peak)	Amplification for 1 Volt Output
Electro-oculogram	dc–100	10uV–5mV	500
Electroretinogram a- and b-wave	0.2–200	0.5uV–1mV	1000
Oscillatory potentials	90–300	0.1uV–100uV	10,000
c-wave	dc–200	0.5uV–1mV	1000
Pattern ERG	0.1–200	0.1uV–10uV	100,000
Visually evoked potentials			
Standard	1–300	0.1uV–20uV	50,000
Fast wavelets	90–300	0.1uV–5uV	200,000
Electroencephalogram	dc–100	2 to 100uV	10,000
Electromyogram	.01–500	50uV–5mV	500
Electrocardiogram	.05–1000	<5mV	500
Galvanic skin response (electrodermal response)	dc–5Hz	<1mV	1000

sure that the isolation amplifier is able to isolate voltages equal to or greater than the largest voltage expected should an electrical accident occur. The technique used is to pass the input signal through a voltage-to-frequency converter. This stage uses little current, which can be provided safely. Then, by using optical means or magnetic transformers, which isolate the input from the main electronics, the frequency is transmitted to a demodulating filter, which returns the frequency to its corresponding voltage. To modulate and demodulate the input voltage, an oscillator or chopper is required. An isolation amplifier cannot handle frequencies greater than one quarter to one tenth of the oscillator frequency, depending on the quality of the amplifier. The frequency of mechanical oscillators or choppers is usually limited to the line frequency (60 Hz in the Americas, 50 Hz in Europe and Asia) but electronic choppers operate easily to several hundred kilohertz.

In addition to protecting the patient from grounding faults, isolation amplifiers can improve signal-to-noise ratios by interrupting ground loops and eliminating capacitance problems, but they may also introduce problems. At high amplifications, the carrier frequency may be seen as noise added to the signal. In poor-quality filters, the higher harmonics or subharmonics of the carrier or chopper frequency may be amplified.

A second means of isolating the patient in the case of a major electrical disaster is to employ low-current, fast-acting fuses in the circuit connecting

TABLE 24–2.
Electronic Noise Sources

Noise Type	Sources	Frequency Characteristics	Reduction Methods
Extrinsic noise	Electrostatic	60 Hz	Serial grounding.
	Magnetic	60 Hz	Eliminate ground loops.
	Radio Frequency	>1k Hz	Shielding; low, equal electrode resistance.
Thermal noise	Sensors and amplifiers	Broadband and random	Differential amplification
1/f Noise	Amplifiers	<100 Hz inversely related to frequency	Differential amplification
Blocking (saturation)	Amplifiers	All frequencies	Reduce gain or noise
Analog-to-digital converters and averaging algorithms	Quantization	<1k Hz	Choice of analog-to-digital converters.
	Sampling jitter	Broadband, nonrandom	
	Aliasing		Filter high frequencies
	Round off errors		
Trigger	Trigger jitter	>10 Hz inversely related to jitter	Stabilize trigger

the patient to the amplifiers. The use of fuses introduces minimal alteration of the frequency or phase information of the signal. However, by increasing the number of connections or junctions through which the unamplified signal passes, the use of fuses may attenuate the signal or introduce noise. Humans can generally sense 1 mamp at 60 Hz, and 5 mamp is the maximum "harmless" current. Therefore, the fuses should be 1 mamp or slightly lower and able to disconnect the circuit in no more than several milliseconds.

Amplifiers are characterized by a number of parameters including bias, frequency response, input impedance, output impedance, gain (sensitivity) vs. noise, slow rate vs. linearity, and roll-off or attenuation vs. common-mode rejection ratio (CMRR).

Direct Current and Alternating Current Amplifiers

Most amplifiers have a resistor and capacitor to separate one stage of the amplifier from the other. One consequence of the resistor-capacitor (RC) network is that direct current (dc) cannot be transmitted from one stage of the amplifier to the other. Very low frequencies are also attenuated.

If the stages of an amplifier are coupled directly (direct-coupled amplifiers), dc and higher frequencies are transmitted from one stage of the amplifier to another. Most amplifier output voltages are not zero, even when the input leads are connected together. This is called an "offset" and occurs at all stages in a dc amplifier; any offset voltage present in an earlier amplifier stage is amplified along with the signal by subsequent amplifier stages, and with high gains, the amplifier may be useless.

This problem is minimized by using a *differential amplifier.* In a differential amplifier, two inputs are provided to the amplifier, and its output is the algebraic difference of the two input signals. Practically, there is always some difference between the two circuits and their offset voltages; therefore, a bias compensation is usually provided to equalize the two halves of the amplifier.

Common Mode Rejection Ratio

Whether dc or alternating current (ac), almost all contemporary physiological amplifiers are differential. In most amplifiers the subtraction of one input from the other occurs at several of the stages of amplification. Any signal that enters both inputs is thereby drastically reduced, e.g., the mains or line frequency. The CMRR is determined by inputting a signal to one amplifier input and then inputting a common signal of the same amplitude to each of the two inputs. The output amplitude should be minimized when the same signal is applied to both inputs. The ratio of the input from one signal input and two signal inputs is the CMRR. With proper adjustment, a CMRR of 100,000:1 is achievable in many amplifiers. Because mains' interference (50 and 60 Hz) is a common source of artifact that may be eliminated by a high CMRR, it is often determined for these frequencies. CMRR is reduced at higher frequencies. Also, the figure given is for identical inputs. If this is not so, e.g., if a corneal lens has a higher resistance than skin, the CMRR will be reduced.

Bias

The bias of an amplifier refers to the voltage output of the amplifier when the input voltage is zero. Amplifier bias should be zero. Frequently, the bias of an amplifier varies with temperature. Therefore, it is wise to measure and if necessary to adjust the bias of an amplifier only after it has been operating for several minutes (or in extreme cases one-half hour). A stable amplifier has minimal variation in bias over time.

Linearity, Gain, and Dynamic Range

The output voltage of an amplifier should be a linear function of the input voltage. The slope of that linear function represents the gain of the amplifier. Real amplifiers are linear only over a range of input voltages at any one gain. The range of input voltages over which a linear function is valid is the dynamic range of the amplifier; 80 to 100 dB is possible.

Input and Output Impedance

The input impedance of a physiological amplifier must be at least 100 times greater than the electrodes to avoid attenuation of the signal or the introduction of extraneous noise. If the impedance of the electrodes is 10 kΩ, the input impedance of the amplifiers must be 1 to 5 MΩ. For these same reasons the output impedance of the amplifier should be low relative to the input impedance of the averager or oscilloscope that serves as the final stage of signal processing. The characteristics of high-input impedance and low-output impedance are a common feature of all commercially available amplifiers for physiological signals.

Frequency Response Function

For a specified gain and input voltage, an amplifier's frequency response function is its output voltage as a function of its input frequency. Based on its frequency response function, amplifiers may be classified into one of four categories based on their filter characteristics: low-pass, high-pass, band-pass, and band-reject (or notch) filters. Figure 24–1 illustrates these categories of filters. Low-pass filters pass frequencies below a certain level and reject higher frequencies. High-pass filters reject frequencies below their cutoff and pass higher frequencies. Band-pass filters pass frequencies between a low and a high frequency and reject others. A band-reject filter rejects frequencies between a high and a low cutoff frequency and pass frequencies lower than the low-frequency cutoff and higher than the high-frequency cutoff.

An ideal filter would have a sharp cutoff. Physically realizable filters have a range of frequencies over which the response is progressively attenuated. The characteristic frequency is where the attenuation is 1/2 or 1/e. The steepness of the change or the roll-off is quantified by the rate of change of attenuation

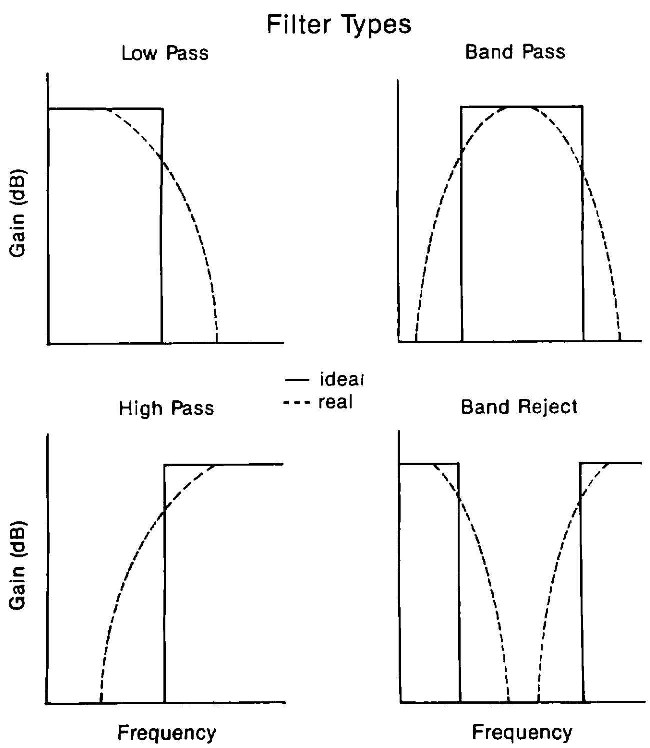

FIG 24–1.
Filters classified by their frequency response characteristics. The four filter types are low-pass, high-pass, band-pass, and band-reject (or notch) filters.

in decibels per octave or decade, outside the characteristic point where the voltage is reduced by 50% (−6 dB) or by −3 dB (70.8%). (A decibel is 10 times the base 10 logarithm of the ratio of two powers. Alternatively, a decibel is 20 times the base 10 logarithm of the ratio of two energies or voltages. Power is energy squared; hence the difference between decibels of power and energy. An octave is the base two logarithm of the ratio of two numbers, i.e., a halving or doubling is one octave. A decade is the base 10 logarithm of the ratio of two numbers. A 3-dB attenuation (−3 dB) of output voltage amplitude is equivalent to a voltage amplitude reduction of 29.2%. A 6-dB-per-octave roll-off indicates that the voltage amplitude decreases by 50% as the frequency doubles or halves. A 24-dB-per octave roll-off indicates that the voltage amplitude decreases by a factor of 15.8 as the frequency increases (or decreases) by a factor of 2.) The roll-off of a filter consisting of a single capacitor and resistor is 3 dB per octave. To obtain steeper roll-offs several strategies can be employed. Complex passive networks, or active filters that incorporate amplifiers to "shape" the filter characteristic, or that use variations on digital techniques may be employed. The penalty paid for roll-off includes phase changes near the characteristic frequency(s), noise, and ringing. Bessel-function filters maintain a constant phase change-vs.-frequency characteristic at the expense of a shallow shoulder. The number of active stages in a filter is referred to as the number of poles. For example, a quadruple filter has four active stages.

Digital and Analog Filters

The first stage of converting the analog signals into digital voltage levels that can be interpreted by the computer is a analog-to-digital converter (ADC). ADCs are the simplest digital filters. The characteristics of these and more complicated digital filters are important because they are becoming a progressively more common feature of the clinical electrophysiology laboratory. A summary of the characteristics of analog and digital filters is presented in Table 24–3. Digital filters may be implemented by either hardware or software.

Any digital filter samples the incoming signal at some frequency. The accuracy of that sampling (quantization and rounding errors) and the appropriateness of the sampling frequency (aliasing and leakage errors) are important. The highest frequency in the input signal cannot be higher than half of the sampling frequency, or lower frequencies will be in-

TABLE 24–3.
Analog and Digital Filters

Property	Analog	Digital
Variables	Continuous in time Continuous in magnitude	Discrete time (samples) discrete magnitudes
Mathematical operations	d/dt, dt, Xk, ±	Delay, Xk, =
Characteristic equations	Linear differential	'Linear' difference (occasionally 'logical-difference)
Characteristic responses	Damped sinusoids, cosinusoids	Samples of damped sinusoids, cosinusoids
Speed	To optical frequencies	To MHz
Imperfections		
'Components'	Initial tolerances Drift Nonlinearity and over-loading	Coefficient rounding Absolutely stable Quantization and over-flow
Noise	Thermal, shot, etc.	Quantizing, aliasing; low level limit cycles

troduced into the signal (aliasing). Even if aliasing is avoided by appropriate low-pass filtering before the digital filter and if the sampling frequency is low relative to the frequencies of interest, voltage from some frequencies will leak or spread across several frequencies.

Despite these considerations, a well-designed digital filter has several advantages over an analog filter. Digital filters are generally more flexible. Both gain and frequency roll-offs are limited only by the digital resolution of the filter. Because the signals are digitized, noise introduced by variations in resistance, capacitance, and inductance in the various stages of the amplifier is eliminated. Finally, in most digital filters used for physiological applications, phase is undistorted. At high-frequency cutoffs below 60 Hz, analog filtered visual evoked potentials (VEPs) are reduced in amplitude and prolonged in latency (Fig 24–2,A and B). Digitally filtered signals are merely reduced in amplitude.[8]

Digital filters may be particularly useful in eliminating noise from averaged signals. For example, responses elicited by pattern reversal contain power mainly at the harmonics of the reversal rate (even harmonics of the reversal frequency). By employing digital filters it is possible to eliminate the noise at other frequencies (Vance Zemon, personal communication, 1988).

One consideration frequently ignored is when an experimenter increases amplification by placing two amplifiers in cascade. (If amplifiers are cascaded, the lower-noise amplifier should be the first stage.) The roll-off of the cascaded amplifiers will be steeper and the −3-dB points different from that of each device on its own. If the high-frequency cutoff f_h and the low-frequency cutoff f_l are the same for each cascaded filter, the high-frequency −3-dB point of the system will be $f_h = f'_h \times \sqrt{[(2 \exp 1/n) - 1]}$. The system's low-frequency −3-dB point will be $f_l = f'_l / \sqrt{[(2 \exp 1/n) - 1]}$. The number of stages that are cascaded is represented by n.

Amplifiers used in clinical visual electrophysiology should amplify the entire frequency range of interest in a specific response. If recording the dc ERG or electro-oculogram (EOG) one should use a band pass from 0 to at least 100 Hz. For normal ac coupling a band pass of 0.3 to 250 Hz is adequate. However, if recording oscillation potentials (OPs) one might choose to record from 90 to 300 Hz. Therefore, one must alter the amplifier's[1] settings to suit the response to be recorded.

The consequences of choosing inappropriate filter settings can be dramatic alterations in response amplitude and/or waveform. Selective attenuation of the high frequencies in a response eliminates high-frequency noise. However, it may also result in a big change in waveform, latency, and amplitude of the response. A reduction of the higher frequencies will generally reduce the amplitude and prolong the latency of a response. Figure 24–2,A presents the effects on averaged VEPs of variations in the high-frequency filter settings. Low-frequency attenuation will eliminate the slowly occurring changes in baseline that may be caused by eye movements or electrodermal responses. Figure 24–2,B indicates the changes in VEPs introduced by increasing the amplifier's low-frequency filter setting. Increasing low-frequency settings will typically reduce the amplitude and latency.

Amplifiers and Phase Distortions

Amplifiers impose a delay in the input signal. Unfortunately, the delay is not constant as a function of signal frequency. Generally, within the frequency range that is unattenuated, the phase is relatively constant across frequency. As frequencies are attenuated, large phase shifts are usually introduced. The changes in phase relationships can introduce latency changes and changes in waveform and amplitude.[3] The magnitude of phase distortion is increased as roll-off is increased. Extending the high-frequency range increases noise, and extending the low range permits slow large oscillations to be recorded, which are thought to be due to eye movements. *Thus it is*

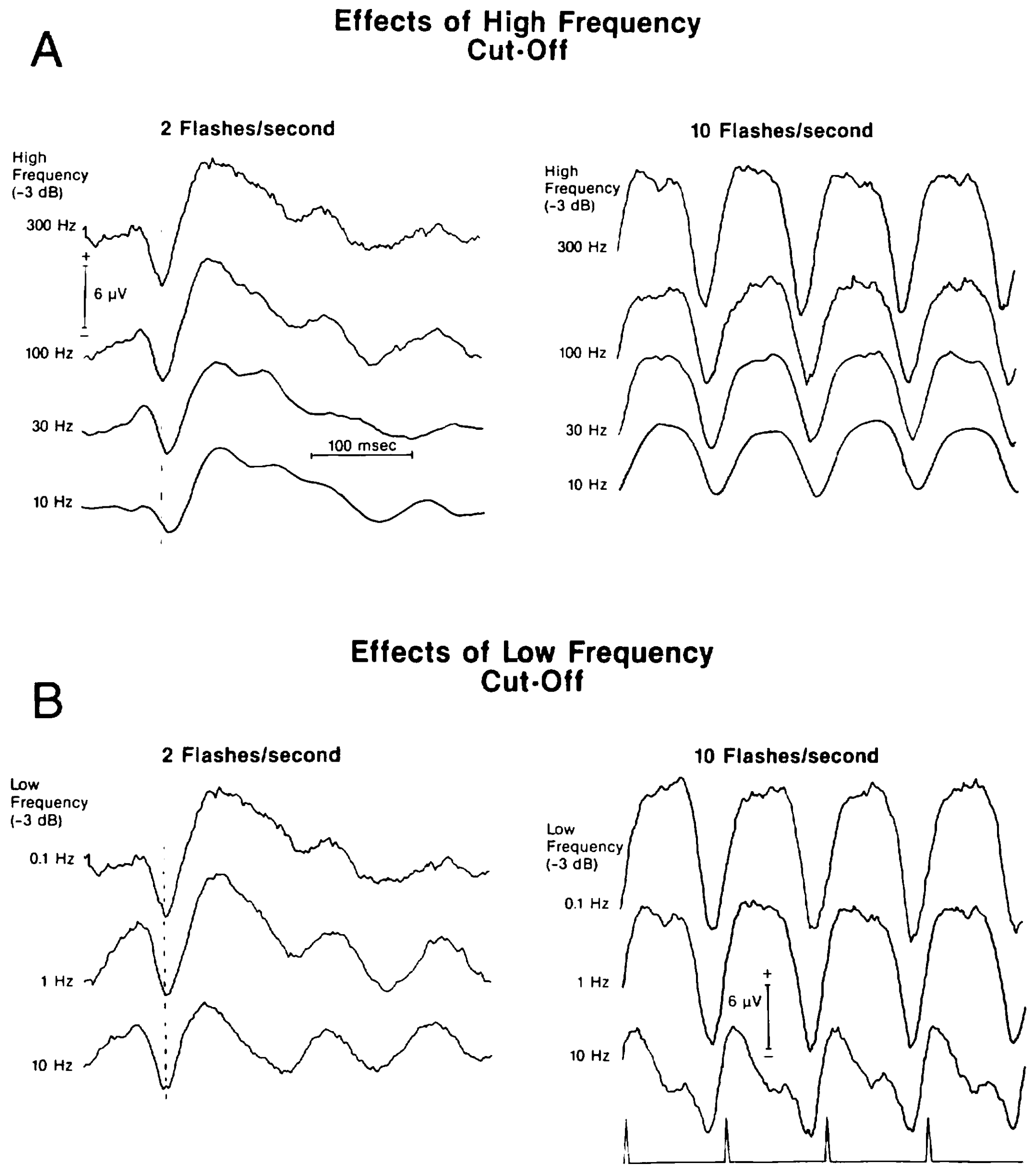

FIG 24–2.
Effects of high- and low-frequency cutoffs on flash VEPs. All records are of 400-ms duration. The *lowest* trace on the *right* indicates the time of flashes. **A**, the effects of the high-frequency cut-off on VEPs elicited by two and ten flashes per second (Grass PS-22, I-2). Notice that with increased analog filtering responses are (1) less noisy, (2) smaller in amplitude, and (3) delayed. **B** illustrates the effects of low-frequency cutoffs on VEPs elicited by two and ten flashes per second. Note that higher low-frequency cut-offs (1) reduce noise, (2) reduce amplitude, (3) decrease peak latencies, and (4) alter waveforms.

desirable to use low- and high-pass filters that have characteristic frequencies outside the region of interest.

The variations in filter settings by different laboratories and their effects on amplitude, phase, and waveform are among the major reasons explaining variation in the absolute values of amplitudes and latencies of responses obtained in different laboratories.

SPECIAL-PURPOSE DATA ACQUISITION SYSTEMS

The amplifiers are usually connected to a special-purpose data acquisition system for recording a visually elicited response. The final stage may be a storage oscilloscope with camera in the case of ERGs, a chart recorder, a lock-in amplifier, or a signal-processing system such as an averager. Although the amplifiers are at the heart of the system, some means of display and storage of data must be found, and there is an increasing need for systems that analyze the visually elicited responses. This has led to the increased sophistication of the equipment available. In the past, much work was done with simple oscilloscopes, and data were captured on film. Chart recorders were also used, but in general, the frequency response of the pens is too low for sophisticated purposes. Now that digital computers are cheap and available, these are commonly used for display and can be used for analysis. They are increasingly displacing the dedicated averagers and lock-in amplifiers that were previously used.

An averager consists of a computer memory of many cells, typically 1,012, that are filled sequentially at fixed intervals after a trigger; thus the cells could be filled at 2-ms intervals and a segment of record of just over 2 seconds obtained. When the trigger is repeated, the contents of each cell are recalled, the new voltage level is added, and the entire value is stored. At the end of *N* such cycles, the value in each cell is divided by *N*, so the contents represent the average. If the records contain both signal plus noise and the noise is random with respect to the signal, the signal-to-noise ratio is reduced by the square root of *N*. The limit of noise reduction is determined by the patient's endurance: for a stimulus that occurs twice a second, 100 repetitions occur in about a minute, and the noise is reduced by a factor of 10; to reduce it 20-fold required 4 minutes, and to reduce it 100-fold required over an hour.

However, much of what is normally considered noise may be electrical signals synchronized to the main's frequency, which may be phase locked to the stimulus. Most noise is due to bad technique, and prolonged averaging is no substitute for this.

Lock-in amplifiers are averagers that basically contain two or four cells. They are used on the assumption that the stimulus is repetitive and that the response is not merely repetitive but approximates a sinusoid. If so, then one can imagine that one cell could be arranged to contain the 180 degrees of the signal that was positive and the second, the 180 degrees that was negative. The difference between the two would be a measure of the amplitude of the signal. However, in general the phase relation between stimulus and response is not known. The problem is overcome by using two more cells that are filled cosinusoidally, i.e., at 90 degrees of phase angle to the first pair. Now two amplitudes of signal have been determined, and by taking advantage of the relationships $\mathrm{Sin}^2\,a + \cos^2 a = 1$ and $\sin a/\cos a = \tan a$, the amplitude and phase of the signal can be determined. In practical instruments, the incoming voltage from the patient is multiplied by a sine or cosine wave generated in the device and the continuous output summed with an integrating amplifier with a variable time constant. The amplifiers have a very high dynamic range, and their careful design ensures the success of the instrument. The assumption is that phase remains stationary; this may not be true of cortical signals, particularly when they are generated on the face of a device like a TV monitor, which is basically intermittent. The lock-in amplifier is potentially faster than an averager in reducing the signal-to-noise ratio because all waveform information is discarded, but in practice, the best results are obtained for high-frequency signals in physical systems, and the results in a slow visual system may be disappointing.

General Characteristics of Special-Purpose Data Acquisition Systems

Some of the major components of a visual signal processor are presented in Figure 24–3. In considering special-purpose data acquisition systems one must consider the entire system. Even the best item is useless unless it is compatible with other parts of the system. The major considerations are how the system's components work together and whether the system satisfies the needs of the individual electrophysiological laboratory.

In order to pass information from an amplifier to a computer one requires an analog-to-digital converter (ADC). With the exception of some lock-in amplifiers, all contemporary data acquisition systems are based on a digital computer. The incoming amplified and filtered analog signal is converted to a digital signal by using an ADC. The digitized input may then be filtered further, averaged, or be acted on in any fashion for which the system is programmed.

An ADC is characterized by its number of bits of resolution. A bit refers to a binary exponent. For example, an 8-bit ADC has 2^8, or 256, steps in its voltage range. If the range is programmable, the gain of the ADC may be varied. If the voltage range is ± 1 V the ADC can resolve 0.0078125 V (1/256). Given an amplification of 10,000, this corresponds to a resolution of 0.78 μV for a single sweep. For most purposes, an 8-bit resolution for the ADC is adequate, although 10- or 12-bit resolution is desirable (a resolution of 0.2 and 0.05 μV respectively assuming a

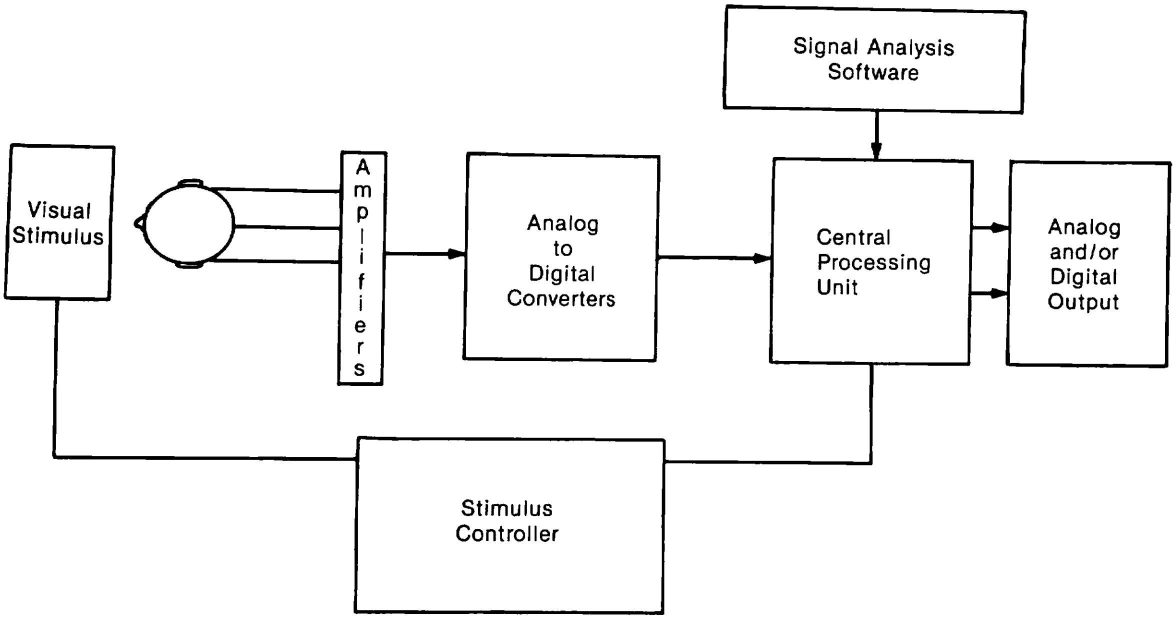

FIG 24–3.
Major components of a typical clinical electrophysiology system.

±1-V range, a gain of 10,000, and a single sweep). Because the analog signal is quantized, additional noise may be introduced into the signal and reduce the signal-to-noise ratio. In addition, the full range of the ADC cannot be employed. Thus, the amplifier gain is set so the trace always remains on the screen. Therefore, the signal of interest will be much smaller and will extend only over, for example, one-fourth screen, or 64 levels or fewer. This will mean that discontinuities can be seen in the waveform.

Most of the currently available commercial systems provide a software package for signal processing. The signal will be averaged or, in some older systems, summed. Signals greater than the ADC range or some predetermined smaller range may be rejected. On better systems this artifact rejection can be turned on or off and can be adjusted within the ADC range. One or more cursors will be available, and one may determine the amplitude and latency of individual locations on the waveform. Frequently, one may transform the waveform by using a variety of mathematical functions such as adding or subtracting a constant, integrating or differentiating the waveform, performing Fourier transforms, performing autocorrelation or cross-correlation functions, and adding or subtracting one waveform from another.

Artifact rejection may be accomplished in several basic ways, including filtering and subtraction of known artifacts. The most common method of artifact rejection available on commercial systems is amplitude rejection. Acquired sweeps containing voltages larger than some preset value are rejected. If the rejection level is adjustable, consideration of information in Table 24–1 may be a useful guide in selecting a rejection level. The basic strategy is to choose a rejection level that rejects no real responses (or some very small percentage) and rejects any large-amplitude artifacts associated with eye movement, blinks, head movement, or muscle tension.

Particular care must be exercised in choosing and using the less common signal processing options such as Fourier transforms. Data are not always presented in easy-to-use forms, and sometimes information is transformed. For example, the old Nicolet Med-80 failed to provide 360 degrees of phase information. A useful feature of some systems is a statistical spread sheet that allows the data to be manipulated so one can sum the amplitudes (or powers) of various frequencies, calculate means and standard deviations, etc.

A certain portion of the computer's memory is allocated for signal processing. The exact algorithm used to perform signal processing varies. Depending on the computer's speed and memory size, some unexpected effects can occur. Some computers have different data channels to divide the same region of memory. For example, if 1,024 data points are allocated for data memory, one channel will have 1,024 data points, two channels will have 512 data points each (1,024/2), and four channels will have 256 each. Other systems have a fixed memory size per channel, so one channel occupies 1,024 memory addresses, two channels occupy 2,048, and so on. If a system has multiple channels, each data channel may be sampled simultaneously, or the channels may be multiplexed. If they are multiplexed, the ADC of each channel is sampled in sequence. Because the order of sampling is fixed, there may be slight but possibly significant phase or time differences between the channels.

Other portions of computer memory will be dedicated to graphics, analysis, and output of the data. Some systems provide cathode ray tube (CRT) or video displays of the incoming signal and/or averages in real time as they occur. Other systems must switch between recording data and displaying data. Therefore, one can obtain only periodic updates of the average without greatly increasing the averaging time.

Many manufacturers offer complete ERG or VEP systems. These include amplifiers, recorders, stimulators, and means of calibration and data analysis. They are often expensive and, because of the time required for development, are also often obsolete. In 1990 a state-of-the art commercial system should have software control of amplifier characteristics; at least 12-bit ADCs with an upper throughput of >30,000 samples per second; 16- or 32-bit central processing units (CPUs); video graphics array (VGA) with a graphics coprocessor allowing screen updates at >4/sec; a command file structure that permits the user to generate a sequence of changes in stimulus and recording parameters to be used in routine tests; a data file structure that permits the storage of multiple records from one patient in a single file; methods of analysis that permit automatic cursoring and trace measurement; recall and comparison of several records from one or more files; and deletion, addition, subtraction, and scaling of records from the same or different files. Many commercial systems do not provide these facilities even though they may boast of those that are less important. Some obsolete systems are, however, so well engineered that they are more reliable and easy to use than their more sophisticated rivals (and they may be less expensive). The prospective purchaser should attempt to get manufacturers to loan the equipment for a real clinical trial before placing a firm order.

An alternative path is to purchase a microcomputer and special-purpose boards and connect them into a system. There are several manufacturers who not only provide the boards but also provide software so that data will appear in designated areas of computer memory. The code for this software is complex, for the boards must run under interrupt control, which is often very difficult to implement. The ADC boards usually contain clocks and counters and digital and analog outputs for controlling laboratory data. It is advisable to buy special graphics display boards with basic software supplied.

Some of the systems come "boxed," and the software will complete averaging routines. Then all the user need do is to implement relatively simple routines that need not take place in "real time." The advantage of this course is that the system can be combined with data bases and arranged according to the user's particular requirements. However, even this software development can be time-consuming and should only be attempted by knowledgeable enthusiasts. Several centers have, however, followed this path and provide their colleagues with the programs.

The time required to perform one operation such as averaging is dependent on the speed of the computer's CPU, the design of the system, and the efficiency of the algorithms used to perform the operation. For example, after a sweep is acquired and manipulated (e.g., divided and added to the previous average), there will be some limited delay between the time the last data point of one sweep is acquired and the time the next data point can be acquired. Across averaging systems, this can vary from microseconds to milliseconds.

Some Questions to Ask

A sample set of questions to ask oneself when examining a system are listed below. These questions are appropriate for both commercial special-purpose systems and personal computers. They are based on problems and needs that a number of users have mentioned. One's needs may be classed into several broad areas: (1) financial and physical limits, (2) equipment compatibility, (3) stimulus suitability, (4) recording suitability, and (5) analysis suitability. Each is considered briefly below. The most general and basic question is, does the system meet your needs? An excellent rule of thumb is to see a system do everything you want it to do before you purchase it. Does the system physically fit into one's laboratory? Is the system within one's financial limits?

When one buys a system, even if it seems complete apart from the cupola, one must determine whether the various components of the system are compatible, whether they can be modified, and whether they perform as desired. For example, if a xenon flash photostimulator serves as the major visual stimulus, does the central computer accept the flash trigger, or alternatively can the computer trigger the photostimulator? Some newer systems accept only transistor-transistor logic (TTL) inputs. If one analyzes single-flash ERGs, can the signal-processing system analyze a single signal? Does the stimulator provide the types of conditions one needs? Frequently, commercial pattern stimulators provide only square-wave pattern reversal of high-contrast checkerboards. Pattern appearance, if provided, is often accompanied by a change in mean luminance. Contrast is often not variable. If one records the ERG with patients in a reclining position, can the cupola be tilted to accommodate this position?

Does the system permit averaging of enough channels to record the responses of interest? Most laboratories seldom use more than two channels, one for each eye or one for the eye and one for the cortical signals. Less frequently one may wish to record three, four, or more channels. Does the system have a satisfactory automated EOG system? Most commercial systems either do not perform the EOG or do a poor job of EOG analysis.

Does the system provide the analysis routines that you need? Almost every system that averages will provide amplitude and latency information for at least one point. For how many points can it provide this information? Can it set up ratios or means of points or their latencies? Do you need to do spectral analysis or perform cross-correlations to calculate kernels? How does the system output the data? Are they plotted? Is a numerical output available? Can the numbers be manipulated if needed? For example, can the values of only stimulus harmonics be presented? Last, if the system does not perform as one wishes, how difficult is it to customize the system's operation? Is the operation modifiable? If frequency information is provided, is it in useful units? One may wish to have access to the real and imaginary components in addition to amplitude (or power) and phase information.

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