chapter 8

Electronic Instrumentation for Radiation Detection Systems

Most of the radiation detectors used in nuclear medicine are operated in a "pulse mode"; that is, they generate pulses of electrical charge or current that are counted to determine the number of radiation events detected. In addition, by analyzing the amplitude of pulses from the detector, it is possible with energy-sensitive detectors, such as scintillation and semiconductor detectors and proportional counters, to determine the energy of each radiation event detected. Selection of a narrow energy range for counting permits discrimination against events other than those of the energy of interest, such as scattered radiation and background radiation or the multiple emissions from a mixture of radionuclides.

Figure 8-1 shows in schematic form the basic electronic components of a nuclear radiation-counting instrument. These components are present in systems ranging from the most simple sample counters to complex imaging instruments. The purpose of this chapter is to describe the basic principles of these components. The electronics for specific systems also are described in Chapters 10, 12 to 14, and 18. Basic principles of electricity and electronics are reviewed in the sources cited in the Bibliography at the end of this chapter.

A. PREAMPLIFIERS

Table 8-1 summarizes the pulse output characteristics of detectors used in nuclear medicine. Most of them produce pulse signals of relatively small amplitude. In addition, most of the detectors listed have relatively high output impedance, that is, a high internal resistance to the flow of electrical current. In handling electronic signals, it is important that the impedance levels of successive components be matched to one another, or electronic interferences that distort the pulse signals may develop and system performance will be degraded.

The purposes of a *preamplifier* (or preamp) are threefold: (1) to amplify, if necessary, the relatively small signals produced by the radiation detector, (2) to match impedance levels between the detector and subsequent components in the system, and (3) to shape the signal pulse for optimal signal processing by the subsequent components.

There are two main types of preamplifier configurations used with radiation detectors: the *voltage-sensitive* preamplifier and the *charge-sensitive* preamplifier. Figure 8-2 shows a simplified diagram of these two configurations. The symbol  represents the signal (pulse)-amplifying component. The resistor (R) and capacitor (C) provide pulse shaping. The signal from the detector is typically a sharply rising pulse of electrical current of relatively short duration ($\lesssim 1$ μsec, except for Geiger-Müller (GM) counters; see Table 8-1). The voltage-sensitive preamp amplifies any voltage that appears at its input. Because radiation detectors are charge-producing devices, this input voltage, V_i, is given by the ratio of the charge, Q, and the

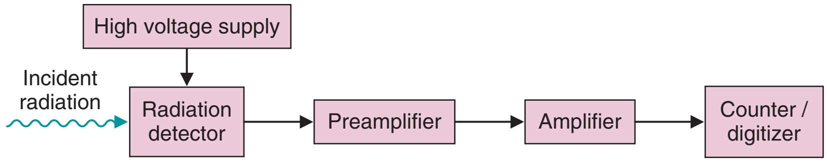


FIGURE 8-1 Schematic representation of the electronic components for a nuclear radiation counting system.

intrinsic capacitance of the detector and other components in the input circuit, C_i:

$$V_i = \frac{Q}{C_i} \tag{8-1}$$

With energy-sensitive detectors, the amount of charge, Q, and thus the amplitude of the voltage V_i are proportional to the energy of the radiation event detected. The output voltage, V_o, in this configuration is approximately

$$V_o \approx -\frac{R_2}{R_1} V_i \tag{8-2}$$

in which R_1 and R_2 are as shown in Figure 8-2. The minus sign indicates that the polarity of the pulse has been changed.

In semiconductor detectors, the input capacitance of the detector is sensitive to operating conditions, particularly temperature. Therefore the proportionality between charge and the voltage seen at the preamp input may not be stable. The charge-sensitive preamplifier overcomes this undesirable feature by using a feedback capacitor of capacitance C_f to integrate the charge from the radiation detector. The resulting output voltage, given by

$$V_o \approx -\frac{Q}{C_f} \tag{8-3}$$

is seen to be independent of the input capacitance, C_i.

The electrical charge leaks off the feedback capacitor through the resistor of resistance R_f, causing the voltage on the capacitor and at the outputs of the amplifier element to decrease exponentially with time t according to

$$V = V_o e^{-t/R_f C_f} \tag{8-4}$$

The product $R_f \times C_f$ is called the *time constant* τ of the pulse-shaping circuit. The voltage decreases exponentially, dropping by 63% of its initial value during one time constant interval (see Fig. 8-2C). When R_f is given in ohms and C_f in farads, the time constant is given in seconds. Typical preamplifier time constants for nuclear medicine detectors (excepting those applications that require fast timing signals) are 20 to 200 µsec.

The amount of amplification provided by the amplifier element of the preamplifier

TABLE 8-1
TYPICAL SIGNAL OUTPUT AND PULSE DURATION OF VARIOUS RADIATION DETECTORS

Detector	Signal (V)	Pulse Duration (µsec)
Sodium iodide scintillator with photomultiplier tube	10^{-1}-1	0.23*
Lutetium oxyorthosilicate scintillator with photomultiplier tube	10^{-1}-1	0.04*
Liquid scintillator with photomultiplier tube	10^{-2}-10^{-1}	10^{-2}*
Lutetium oxyorthosilicate scintillator with avalanche photodiode	10^{-5}-10^{-4}	0.04*
Direct semiconductor detector	10^{-4}-10^{-3}	10^{-1}-1
Gas proportional counter	10^{-3}-10^{-2}	10^{-1}-1
Geiger-Müller counter	1-10	50-300

*Mean decay time.

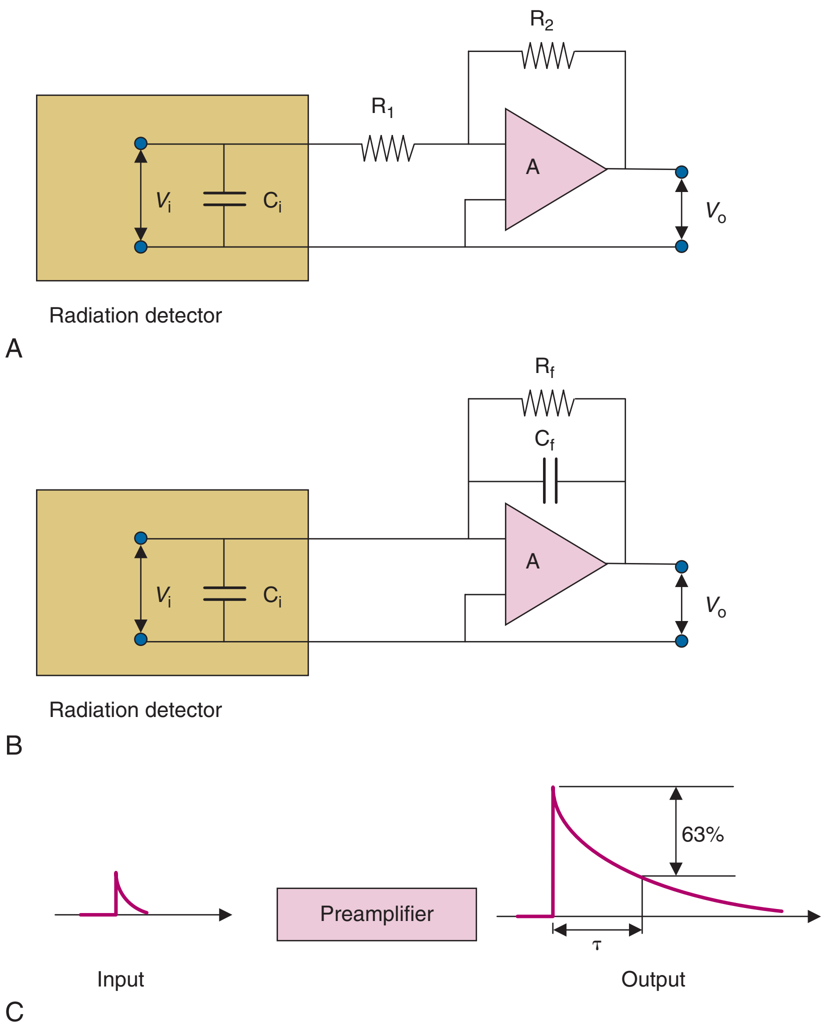


FIGURE 8-2 *A,* Simplified circuit diagram of a voltage-sensitive preamplifier. The output voltage is determined by the amount of charge from the radiation detector, the input capacitance C_i, and the resistances R_1 and R_2. *B,* Simplified circuit diagram of a charge-sensitive preamplifier. The output voltage is determined by the charge from the radiation detector and the value of the feedback capacitor C_f. The symbol —A▷— represents a voltage or current amplifying element. *C,* Input and output pulse signals for a charge-sensitive preamplifier. $\tau = (R_f \times C_f)$ is the time constant of the pulse-shaping circuit.

varies with the type of detector. With scintillation detectors that use photomultiplier (PM) tubes, the PM tube already provides a considerable degree of amplification (10^6-10^7); thus relatively little additional amplification may be needed. Typically, a preamplifier *gain factor* (ratio of output to input amplitudes) of 5-20 is used for these detectors; however, some NaI(Tl):PM tube systems employ no preamplifier gain (gain factor of 1).

Detectors producing smaller signals, such as semiconductor detectors, may require a relatively high level of preamplifier gain, perhaps in the range of 10^3-10^4. It is not a trivial problem to design an amplifier that provides this amount of gain without introducing "noise signals" and temperature-related gain instabilities. Most of the modern high-gain preamplifiers employ *field-effect transistors*, which provide the desired low-noise and temperature-stability characteristics.

For energy-sensitive detectors, the preamplifier must operate in a *linear* fashion; that is, the amplitude of the signal out must be directly proportional to the amount of charge delivered to it by the detector. This preserves the relationship between pulse amplitude and energy of the radiation event detected, so that subsequent energy analysis may be applied to the pulse signals.

For the best results, the preamplifier component should be located as close as physically possible to the detector component. This maximizes the electronic signal-to-noise ratio (SNR) by amplifying the signal before additional noise or signal distortion can occur in the long cable runs that frequently separate the detector from the rest of the signal-processing components. This is particularly critical for detectors with small output signals (e.g., semiconductor detectors or scintillation detectors used for detecting low-energy radiations). It also is important for applications in which energy resolution is critical (see Chapter 10, Section B.7). Frequently, detectors and preamplifiers are packaged and sold as single units.

B. AMPLIFIERS

1. Amplification and Pulse-Shaping Functions

The amplifier component of a nuclear counting instrument has two major functions: (1) to amplify the still relatively small pulses from the preamp to sufficient amplitude (volts) to drive auxiliary equipment (pulse-height analyzers, scalers, etc.), and (2) to reshape the slow decaying pulse from the preamp into a narrow one to avoid the problem of pulse pile-up at high counting rates and to improve the electronic SNR.

The gain factor on an amplifier may range from ×1 to ×1000. Usually it is adjustable, first by a coarse adjustment (i.e., ×2, ×4, ×8) and then by a fine gain adjustment providing gain factors between the coarse steps. The coarse gain adjustment permits amplification of pulses over a wide range of amplitudes from different detectors and preamplifiers to the maximum output capability of the amplifier. The fine gain adjustment permits precise calibration of the relationship between amplifier output pulse amplitude (volts) and radiation energy absorbed (keV or MeV). For example, a convenient ratio might be 10 V of pulse amplitude per 1 MeV of radiation energy absorbed in the detector.

Pulse shaping—i.e., pulse shortening—is an essential function of the amplifier. The output of the preamp is a sharply rising pulse that decays with a time constant of about 50 μsec, returning to baseline after approximately 500 μsec. Thus if a second pulse occurs within 500 μsec, it rides on the tail of the previous pulse, providing incorrect amplitude information (Fig. 8-3). The system could not operate at counting rates exceeding a few hundred events per second without introducing this type of amplitude distortion.

The pulse-shaping circuits of the amplifier must provide an output of cleanly separated pulses, even though the output pulses from the preamp overlap. It must do this without distorting the information in the preamplifier signal, which is, mainly, (1) pulse amplitude

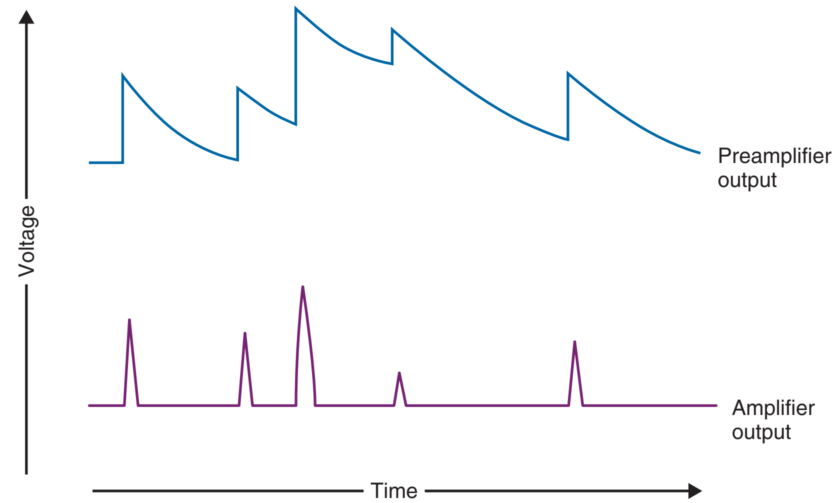


FIGURE 8-3 Sequence of pulse signals in a radiation counting system. *Top,* Relatively long preamplifier time constant results in overlapping of pulse signals. *Bottom,* Amplifier output pulses have been shortened but without significant loss of amplitude or timing information.

(proportional to the energy of radiation event for energy-sensitive detectors) and (2) rise time (time at which the radiation event was detected). An additional function of the pulse-shaping circuits is to discriminate against electronic noise signals, such as microphonic pickup and 50- to 120-Hz power line frequency.

The most common methods for amplifier pulse shaping are resistor-capacitor (RC), gaussian, and delay-line methods. The RC technique, commonly referred to as *RC shaping,* is described to illustrate the basic principles. More detailed circuit descriptions are found in the sources cited in the Bibliography at the end of this chapter.

2. Resistor-Capacitor Shaping

Basic RC pulse-shaping circuits are shown in Figure 8-4. When a sharply rising pulse of relatively long duration (e.g., preamplifier output pulse) is applied to a capacitor-resistor (CR), or *differentiation circuit* (see Fig. 8-4A), the output is a rapidly rising pulse that decays with a time constant τ_d determined by the RC product of the circuit components (Equation 8-4). The amplitude of the output pulse depends on the amplitude of the sharply rising portion of the input pulse and is insensitive to the "tail" of any preceding pulse. Note that a CR differentiation circuit also is used for pulse shaping in the preamplifier; however, the time constants used in the preamplifier circuits are much longer than those used in the amplifier. Figure 8-4A also illustrates how the CR circuit discriminates against low-frequency noise signals.

Figure 8-4B shows an RC, or *integration* circuit. (Note that differentiation and integration differ only by the interchanging of the resistor R and the capacitor C.) When a sharply rising pulse is applied to this circuit, the output is a pulse with a shape described by

$$V_o(t) = V_i(1 - e^{-t/RC}) \tag{8-5}$$

where V_i is the amplitude of the input pulse and RC = τ_i is the integration time constant of the circuit. This circuit discriminates effectively against high-frequency noise, as illustrated in Figure 8-4B.

Figure 8-5A shows a pulse-shaping circuit combining differentiation and integration stages. When the time constants of the two circuits are equal ($\tau = \tau_i = \tau_d$), the output is a pulse that rises to a maximum value in a time equal to 1.2τ and then decays to approximately zero in 7τ. The maximum amplitude of the output pulse is determined by the amplitude of the input pulse. For scintillation and semiconductor detectors, a time constant in the range τ ~ 0.25-5.0 μsec usually is chosen. Thus the output pulse is shortened considerably relative to the pulse from the preamplifier (50-500 μsec) and is suitable for high counting rate applications. Except for a very small negative overshoot at the end of the pulse, the output pulse from this circuit has only one polarity (positive in Fig. 8-5A) and is called a *unipolar* output.

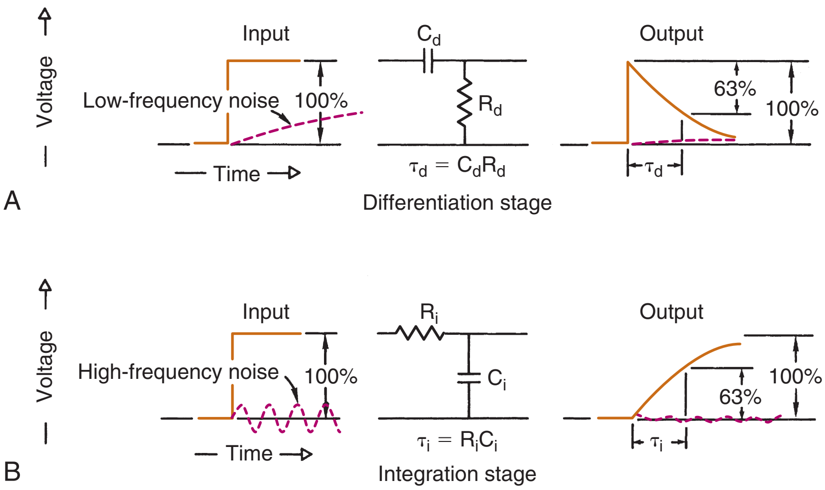


FIGURE 8-4 Basic resistor-capacitor pulse-shaping circuits. *A,* Differentiation provides a sharply rising output signal that decays with time constant τ_d and discriminates against low-frequency noise. *B,* Integration circuit provides an output pulse that rises with time constant τ_d and discriminates against high-frequency noise.

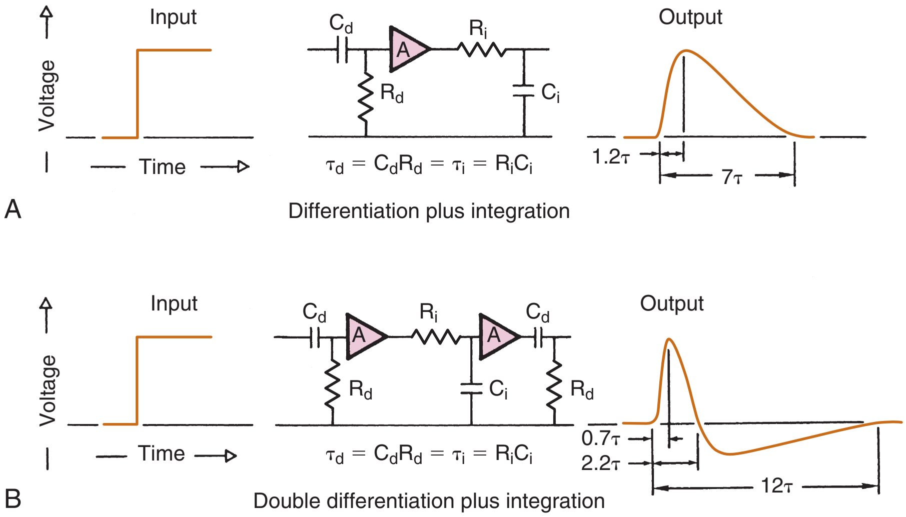


FIGURE 8-5 Resistor-capacitor pulse-shaping circuits combining differentiation and integration stages. *A,* Differentiation followed by integration. *B,* Differentiation-integration-differentiation circuit.

Figure 8-5B illustrates another type of shaping, called *double differential* shaping. The output pulse from this circuit has both positive and negative components and therefore is a *bipolar* pulse. For equal time-constant values, the bipolar output pulse has a shorter rise time and positive portion and a longer total duration than the unipolar output pulse. Unipolar pulses are preferred for signal-to-noise characteristics and are used where energy resolution is important. Bipolar pulses are preferred for high counting rate applications.

Research-grade amplifiers generally are provided with adjustable pulse-shaping time constants. A longer time constant provides better pulse amplitude information and is preferred in applications requiring optimal energy resolution, for example, with semiconductor detectors (Chapter 10, Section C.1). A shorter time constant is preferred in applications requiring more precise event timing and higher counting rate capabilities, such as scintillation cameras (Chapters 13 and 14) and coincidence detection of positron annihilation photons (Chapter 18).

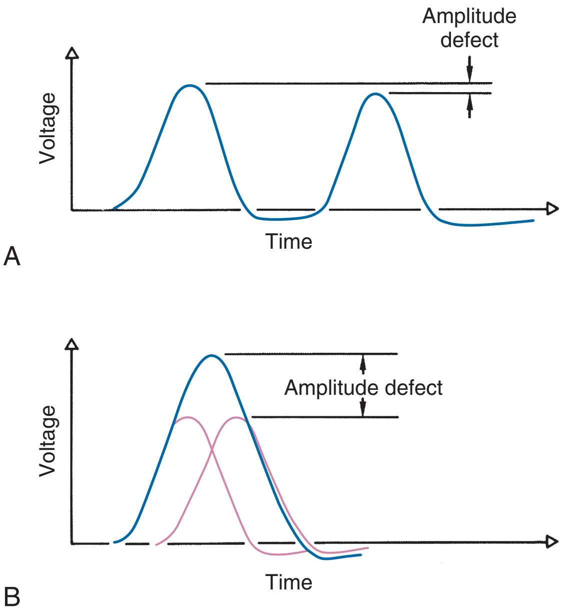


FIGURE 8-6 *A,* Schematic representation of baseline shift, caused by a pulse riding on the "tail" of a preceding pulse. *B,* Pulse pile-up effects for two pulses occurring very close together in time.

3. Baseline Shift and Pulse Pile-Up

Baseline shift and *pulse pile-up* are two practical problems that occur in all amplifiers at high counting rates. Baseline shift is caused by the negative component that occurs at the end of the amplifier output pulse. A second pulse occurring during this component will be slightly depressed in amplitude (Fig. 8-6A). Inaccurate pulse amplitude and an apparent shift (decrease) in energy of the detected radiation event are the result (see Fig. 10-9).

Special circuitry has been developed to minimize baseline shift. This is called *pole zero cancellation,* or *baseline restoration.* This type of circuitry is employed in modern scintillation cameras to provide a high counting rate capability, particularly for cardiac studies. These circuits are described in the sources cited in the Bibliography at the end of this chapter.

At high counting rates, amplifier pulses can occur so close together that they fall on top of each other. This is referred to as *pulse pile-up* (Fig. 8-6B). When this happens, two pulses sum together and produce a single pulse with an amplitude that is not representative of either. Pulse pile-up distorts energy information and also contributes to counting losses (dead time) of the detection system, because two pulses are counted as one (Chapter 11, Section C).

Both baseline shift and pulse pile-up can be decreased by decreasing the width of the amplifier pulse (i.e., the time constant of the amplifier); however, shortening of the time constant usually produces poorer SNR and energy resolution. It is generally true that all the factors that provide high count rate capabilities in amplifiers also degrade energy resolution (Chapter 10, Section B.7).

Generally, amplifiers with double differentiation or double delay-line bipolar outputs are employed with NaI(Tl):PM tube detectors that must handle high counting rates. The bipolar output helps to avoid baseline shift problems, allowing good pulse-height determination at high counting rates. In addition, short time constants of 0.025-0.5 μsec are used. The relatively poor inherent energy resolution of NaI(Tl):PM tube detectors is not affected significantly by this type of amplifier, and a high counting rate capability is provided. Semiconductor detectors usually require much more sophisticated amplifiers, with unipolar pulse shaping, longer time constants (0.5-8 μsec), and circuits for stabilizing the baseline to maintain their exceptionally good energy resolution at high counting rates (Chapter 10, Section C.1).

C. PULSE-HEIGHT ANALYZERS

1. Basic Functions

When an energy-sensitive detector is used [e.g., NaI(Tl):PM tube or a semiconductor detector], the amplitude of the voltage pulse from the amplifier is proportional to the amount of energy deposited in the detector by the detected radiation event. By examining the amplitudes of amplifier output pulses, it is possible to determine the energies of detected radiation events. Selective counting of only those pulses within a certain *amplitude* range makes it possible to restrict counting to a selected *energy* range and to discriminate against background, scattered radiation, and so forth outside the desired energy range (see Fig. 10-6).

A device used for this purpose is called a *pulse-height analyzer* (PHA). A PHA is used to select for counting only those pulses from the amplifier falling within selected voltage amplitude intervals or "channels." If this is done for only one channel at a time, the device is called a *single-channel analyzer* (SCA). A device that is capable of analyzing simultaneously within many different intervals or channels is called a *multichannel analyzer* (MCA). Basic principles of these instruments are discussed in the following sections.

2. Single-Channel Analyzers

An SCA is used to select for counting only those pulses from the amplifier that fall within a selected voltage amplitude range. At this stage in the system voltage amplitude is proportional to radiation energy deposited in the detector, so it is equivalent to selecting an energy range for counting. Modern amplifiers produce output pulses with amplitudes in the range of 0-10 V. Therefore the voltage selection provided by most SCAs is also in the 0- to 10-V range.

An SCA has three basic circuit components (Fig. 8-7): a *lower-level discriminator* (LLD), an *upper-level discriminator* (ULD), and an *anticoincidence* circuit. The LLD sets a threshold voltage amplitude V (or energy E) for counting. The ULD sets an upper voltage limit $V + \Delta V$ (or $E + \Delta E$). The difference between these voltages (or energies), ΔV (or ΔE), is called the *window width*. Usually the LLD and ULD voltages are selected by means of potentiometer or other electronic controls that are adjusted to select some fraction of a 10-V reference voltage.

The LLD and ULD establish voltage levels in electronic circuits called *comparators*. As their name implies, these circuits compare the amplitude of an input pulse with the LLD and ULD voltages. They produce an output pulse only when these voltages are exceeded. Pulses from the comparator circuits are then sent to the anticoincidence circuit, which produces an output pulse when only one (LLD) but not both (ULD and LLD) pulses are present (see Fig. 8-7). Thus only those input pulses with amplitudes between V and $V + \Delta V$ (i.e., within the selected energy window) cause output pulses from the SCA.

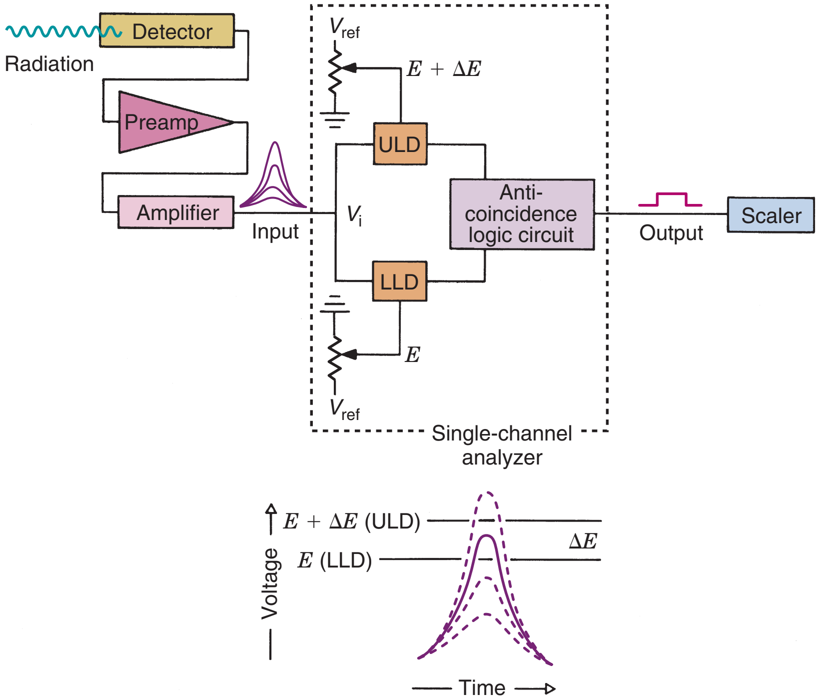


FIGURE 8-7 Principles of a single-channel pulse-height analyzer. *Top,* Electronic components that are used to generate an output pulse only when pulse amplitude falls between voltages established by lower-level discriminator (LLD) and upper-level discriminator (ULD) circuits. These voltages are an adjustable portion of a reference voltage V_{ref}. *Bottom,* LLD and ULD voltages in effect establish an energy range (E to $E + \Delta E$) for counting because pulse voltage amplitude V is proportional to radiation event energy E. Only pulse signals within the ΔE bracket (solid line) are counted.

The SCA output pulses are used to drive counters, rate meters, and other circuits. The output pulses from the SCA are all of the same amplitude and shape (typically 4-V amplitude, 1-μsec duration). Their amplitudes no longer contain information about radiation energy, because this information has already been extracted by the SCA.

Commercially made SCAs frequently have two front-panel controls: a lower-level (voltage V or energy E) control and a window (ΔV or ΔE) control. The LLD control is also called the *base level* on some instruments. The upper-level voltage is determined by electronic summation of lower-level and window voltages on these instruments.

Some instruments include "percent window" selections. With these instruments, the window width voltage is selected as a certain percentage of the window center voltage. (The window center voltage is the lower level voltage V plus one half of the window voltage, $\Delta V/2$.) For example, if one were to set the window center at 2 V with a 20% window, the window width would be 0.4 V (20% of 2 V), and the window would extend from 1.8 to 2.2 V.

On many nuclear medicine instruments, manufacturers have provided pushbuttons to select automatically the analyzer lower level and window voltages appropriate for commonly used radionuclides. In these systems, the pushbuttons insert calibrated resistance values into the SCA circuitry in place of the variable resistances shown in Figure 8-7.

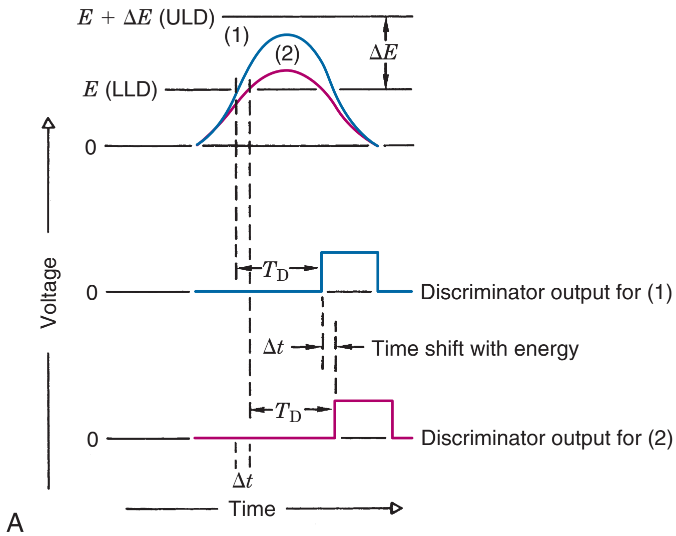
Another possibility on some instruments is to remove the upper-level voltage limit entirely. Then all pulses with amplitudes exceeding the lower-level voltage result in output pulses. An analyzer operated in this mode is sometimes called a *discriminator.* Many auxiliary counting circuits (e.g., scalers and rate meters) have a built-in discriminator at their inputs to reject low-level electronic noise pulses.

3. Timing Methods

Accurate time placement of the radiation event is important in some nuclear medicine applications. For example, in the scintillation camera (Chapter 13), accurate timing is required to identify the multiple phototubes involved in detecting individual radiation events striking the NaI(Tl) crystal (i.e., for determining the location of each event with the position logic of the camera). Even more critical timing problems occur in coincidence counting of positron annihilation photons (Chapter 18) and in the liquid scintillation counter (Chapter 12, Section C).

Most SCAs used in nuclear medicine employ *leading-edge* timing. With this method, as shown in Figure 8-8A, the analyzer output pulse occurs at a fixed time T_D following the instant at which the rising portion of the input pulse triggers the LLD. This type of timing is adequate for many applications; however, it suffers a certain amount of inaccuracy [5 to 50 nsec with NaI(Tl) coupled with a PM tube] because the timing of the output pulse depends on the amplitude of the input pulse. This timing variation Δt is called *timing walk*.

More precise timing is obtained with analyzers employing fast timing techniques. One such method is called *zero-crossover* timing (Fig. 8-8B). This method requires a bipolar input pulse to the SCA. The output pulse occurs at the time of crossover of the bipolar pulse from a positive to a negative voltage



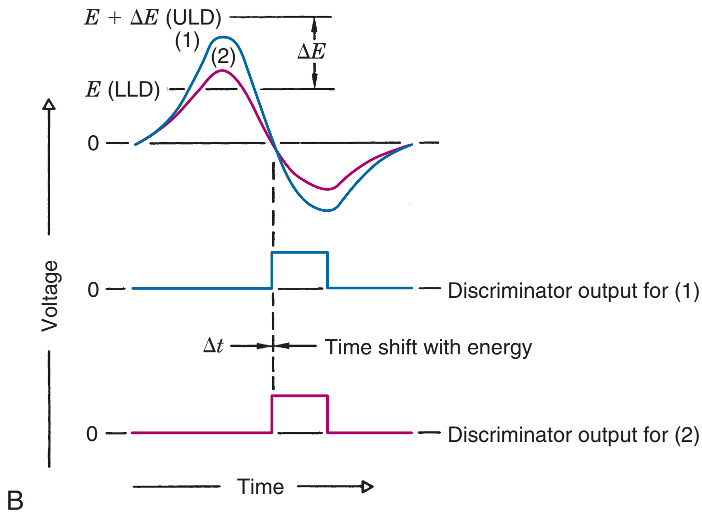


FIGURE 8-8 Examples of timing methods used in pulse-height analyzers. *A,* With leading-edge timing, the output pulse occurs at a fixed time T_D after the leading edge of the pulse passes through the lower-level discriminator (LLD) voltage. *B,* With zero-crossover timing, output pulse occurs when the bipolar input pulse passes through zero. The latter is preferred for precise timing because there is very little time shift with different pulse amplitudes (energy). ULD, upper-level discriminator.

value. The zero-crossover method is much less sensitive to pulse amplitude than the leading-edge method and can provide timing accuracy to within ± 4 nsec with NaI(Tl):PM tube detectors. Other fast-timing methods include *peak detection* and *constant fraction* techniques. They are discussed in the sources cited in the Bibliography at the end of this chapter.

4. Multichannel Analyzers

Some applications of pulse-height analysis require simultaneous recording of events in multiple voltage or energy windows. One approach is to use many SCAs, each with its own voltage window. For example, some imaging devices have two or three independent SCAs to record simultaneously the multiple γ-ray energies emitted by nuclides such as ^{67}Ga; however, this approach is unsatisfactory when tens or even thousands of different windows are required, as in some applications of pulse-height spectroscopy (Chapter 10). Multiple SCAs would be expensive, and the adjusting and balancing of many different analyzer windows would be a very tedious project.

A practical solution is provided by an MCA. Figure 8-9 demonstrates the basic principles. The heart of the MCA is an *analog-to-digital converter* (ADC), which measures and sorts out the incoming pulses according to their amplitudes. The pulse amplitude range, usually 0-10 V, is divided by the ADC into a finite number of discrete intervals, or *channels,* which may range from 100 in small analyzers to as many as 65,536 (2^{16}) in larger systems. Thus, for example, the ADC in a 1000-channel analyzer would divide the 0- to 10-V amplitude range into 1000 channels, each 10 V/1000 = 0.01 V wide: 0-0.01 V corresponding to channel 1, 0.01-0.02 V to channel 2, and so forth. The ADC converts an *analog* signal (volts of pulse amplitude),

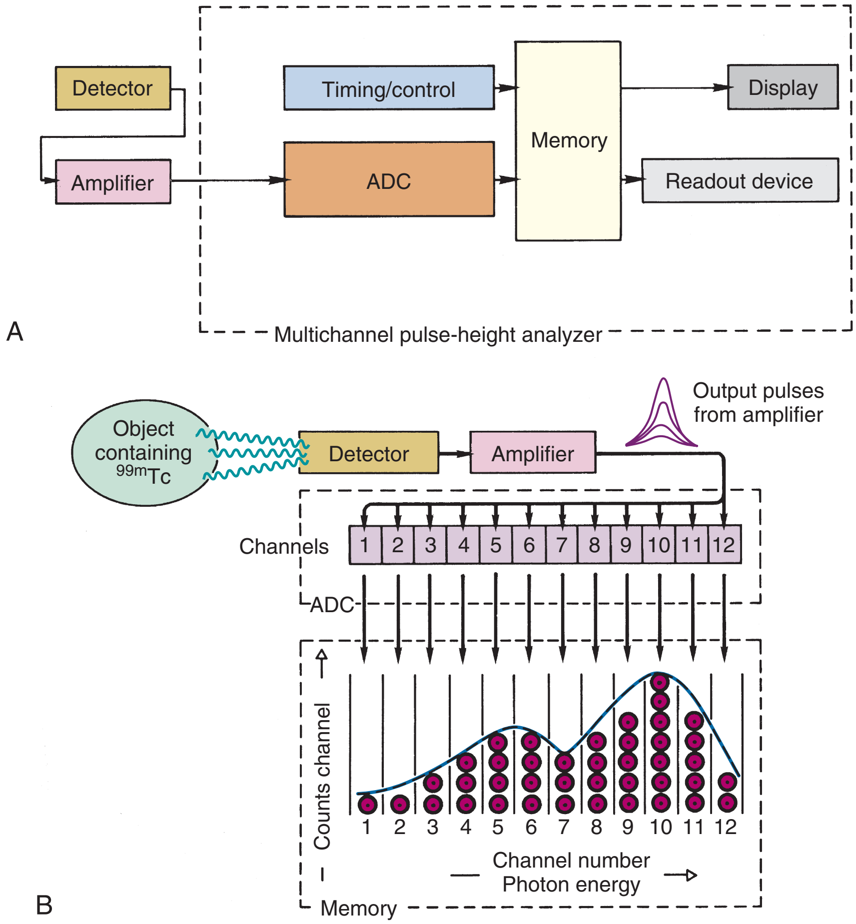


FIGURE 8-9 Principles of a multichannel analyzer (MCA). *A,* Basic components. *B,* Example of pulse sorting according to amplitude for radiation events detected from an object containing ^{99m}Tc. ADC, analog-to-digital converter.

which has an essentially infinite number of possible different values, into a *digital* one (channel number), which has only a finite number of integer values (see Fig. 8-9). In addition to their use in counting systems, ADCs are also used in the interface between nuclear medicine imaging detectors and computer systems.

For each analyzer channel, there is a corresponding storage location in the MCA *memory*. The MCA memory counts and stores the number of pulses recorded in each analyzer channel. The number of memory storage locations available determines the number of MCA channels. The sorting and storage of the energy information from radiation detectors with an MCA are used to record the *pulse-height spectrum* (counts per channel versus channel number, or energy), as shown in Figure 8-9B.

MCAs also are available as boards that plug into personal computers. The computer is used to program the settings on the MCA (i.e., number of channels to be used and voltage range to be selected) and also to control acquisition of data from the detector (acquisition start time and acquisition duration). The computer also is used to display the resulting data (number of counts per MCA channel for the measurement period) that are transferred from the MCA card onto the computer's hard disk. Many MCA boards are capable of receiving data from several inputs at once and can therefore be used to acquire and display data from several detector units simultaneously.

Two types of ADCs are commonly used in nuclear medicine for MCAs and for interfaces between scintillation cameras and computers. In the *Wilkinson,* or ramp, converter (Fig. 8-10), an input pulse from the radiation detector and amplifier causes an amount of charge to be deposited onto a capacitor at the ADC input. The amount of charge deposited depends on the pulse amplitude or energy. The capacitor discharges through a resistor, with a relatively long RC time constant. While the capacitor is discharging, a gate pulse activates a clock oscillator to produce a train of pulses that are counted in a counting circuit. When the capacitor has been discharged, the gate pulse is terminated and the clock oscillator is turned off. The number of clock pulses counted is determined by the capacitor discharge time, which in turn is determined by the initial amount of charge deposited on the capacitor and thus depends on the amplitude of the input pulse. The MCA control circuits

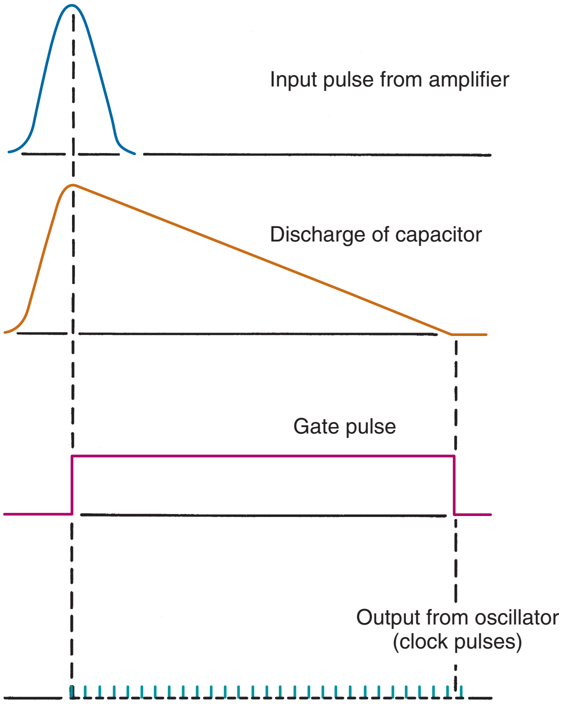


FIGURE 8-10 Principles of analog (pulse amplitude) to digital (channel number) conversion in the Wilkinson, or ramp, converter. Input pulse is used to charge a capacitor, and discharge time, which is proportional to pulse amplitude, is measured using a clock oscillator.

increment by one count the memory channel corresponding to the number of clock pulses counted, then clear the input circuitry and prepare the MCA to accept the next input pulse.

In the *successive approximation* (SA) converter, digitization occurs by comparing the pulse amplitude with a selected sequence of voltage levels. The first comparison level is equal to one half of the full-scale (maximum) value. If the pulse amplitude is greater than this level, the first digital "bit" is set to "1"; if not, it is set to "0." The comparison voltage level then is either increased or decreased by one half of its initial level, (i.e., to 25% or 75% of full scale) depending on whether the pulse amplitude did or did not exceed the initial level. The comparison is repeated and the second digital bit is recorded as "1" or "0," depending on whether the pulse amplitude is greater or smaller than the new comparison voltage level. The comparisons are repeated through several steps, each time decreasing the voltage increment by one half. The final set of bits provides a binary (base 2) representation for the amplitude of the input pulse.

For both the ramp and SA converters, the output is represented as a binary number between 0 and 2^n. The value of n determines the number of possible digital levels into which the input pulse amplitude can be converted. For example, an 8-bit converter, for which $n = 8$, divides the input range into 256 digital levels ($2^8 = 256$), a 10-bit converter into 1024 levels ($2^{10} = 1024$), and so forth. The larger the number of bits, the more precisely the ADC can determine the pulse amplitude. Thus an 8-bit converter can determine amplitude to a precision of one part in 256, a 10-bit converter to one part in 1024, and so forth. Generally, a larger number bit is favored for precision, but the digital conversion process then requires somewhat more time and the digitized values for pulse amplitude require greater amounts of computer storage space. Most nuclear medicine studies can be performed with 8-bit converters, but 10- and 12-bit converters also are used for situations in which precision is a prime concern (e.g., high-resolution energy spectroscopy with semiconductor detectors; see Chapter 10, Section C.1).

A finite amount of time is required for the digital conversion processes described earlier. For example, for a 10-bit (1024-channel) ramp converter with a 100-MHz (10^8 cycle/sec) clock, the capacitor discharge time required for an event in the 1000th channel (1000 clock pulses) is 1000 pulses ÷ 10^8 pulse/sec = 10^{-5} sec or 10 μsec. For an SA converter, time is needed for each of the voltage comparisons; for example, a 10-bit SA converter must perform a sequence of 10 voltage comparisons, each requiring a fraction of a microsecond to complete.

In addition to the conversion process, time is required to increment the memory location, reset the clock pulse counter on comparison voltage levels, and so on. The ADC can therefore be a "bottleneck" in MCAs as well as in the digital conversion process for signals from a scintillation camera. Modern ADCs, however, can digitize events at rates in excess of 1 million counts/sec; therefore ADC speed need not be a limiting factor for applications involving NaI(Tl) detectors, for which the primary time limitation is the decay time of the individual scintillation events.

Most MCAs have additional capabilities, such as offset or expansion of the analyzer voltage range and time histogram capabilities. These are discussed in detail in MCA operator manuals. Some scintillation cameras, well counters, and liquid scintillation counters contain MCAs that are used to examine and select energy windows of interest.

D. TIME-TO-AMPLITUDE CONVERTERS

In certain applications it is useful to be able to measure the distribution of time differences between incoming pulses from a detector, much in the same way that an MCA measures the distribution of energies deposited in the radiation detector. For example, we might wish to use two opposing scintillation detectors to view a positron-emitting radionuclide and to measure the time difference between the detection of two annihilation photons. If the difference is "small" ($\lesssim$ a few nanoseconds), they are highly likely to arise from a single positron annihilation event, whereas if the difference is not small, they probably reflect two independent events.

The *time-to-amplitude converter* (TAC) produces an output signal with a voltage proportional to the time difference between two *logic pulses* supplied to the input. The logic pulses typically come from the output of a discriminator or SCA (see Section C.2) attached to a radiation detector and have a standard box shape with a well-defined amplitude and duration. The concepts of a TAC are illustrated in Figure 8-11. The first logic pulse (known as the *START signal*) is used to start the charging of a capacitor by a constant current source. The second logic pulse (the *STOP signal*) is used to terminate the charging of the capacitor. Because the capacitor is charged from a constant current source, the voltage across the capacitor increases linearly with time and is therefore proportional to the time interval between the START and the STOP signals.

The voltage across the capacitor determines the amplitude of the output voltage pulse of the TAC and is therefore also proportional to the time interval between the two logic pulses. The output pulses from the TAC can be fed to a standard MCA to produce a histogram of the distribution of time differences between the two logic pulses. The MCA is calibrated in terms of time units by supplying the TAC with pulses with a known time interval between them. Alternatively, they can be used to set a timing threshold for accepting or rejecting two detected events as being coincident (e.g., originating from the same nuclear decay). Following the STOP

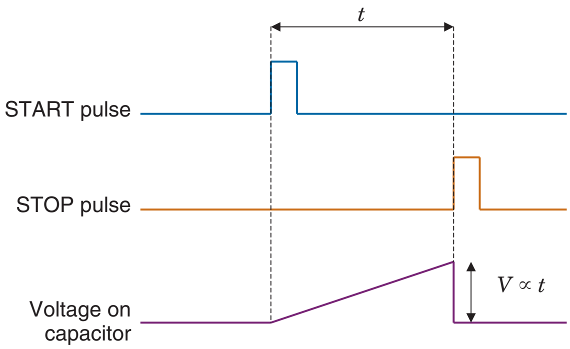


FIGURE 8-11 Principles of a time-to-amplitude converter (TAC). A START pulse is used to start the charging of a capacitor by a constant current source, which is terminated by the STOP pulse. The voltage developed across the capacitor is proportional to the time interval between the START and STOP pulses.

signal, the TAC is reset by discharging the capacitor, so it is ready for the next START signal.

E. DIGITAL COUNTERS AND RATE METERS

1. Scalers, Timers, and Counters

Digital counters are used to count output signals from radiation detectors after pulse-height analysis of the signals. A device that counts only pulses is called a *scaler*. An auxiliary device that controls the scaler counting time is called a *timer*. An instrument that incorporates both functions in a single unit is called a *scaler-timer*. These devices are often referred to under the generic name of *counters*. The number of counts recorded and the elapsed counting time may be displayed on a visual readout, or, more commonly, the output of the scaler-timer may be interfaced to a personal computer automated data processing. Computer-driven counters, which reside on a board that is placed inside of the computer, are also common.

Figure 8-12 shows schematically the basic elements of a scaler-timer. The input pulse must pass through an electronic "gate" that is opened or closed by front-panel switches or pushbutton controls that select the mode of operation. When the gate is open, the pulses pass through to decimal counter assemblies (DCAs). Each DCA records from zero to nine events. The tenth pulse resets the counter assembly to zero and sends a pulse to the next DCA in the series. The number of counter assemblies determines the number of decades of scaler capacity. Thus a six-decade scaler has six DCAs and a counting capacity from 0 to 999,999 counts. (Usually the "1-millionth count" resets the scaler to "0" and turns on an overflow light). Data from each DCA are transferred to the display for continuous visual readout of the number of counts recorded during the counting interval.

As shown in Figure 8-12, the scaler gate can be controlled in a number of different ways. In *preset-time* mode, the gate is controlled by a timer circuit (usually an oscillator-driven clock circuit) that opens the gate for a counting time selected by front-panel switches, or by a computer. The counting interval begins when a "start" button is depressed and is terminated automatically when the selected counting time has elapsed. In *preset-count* (PSC) mode, the counting interval ends when a preselected number of counts has been recorded. PSC mode is used when one wants to achieve the same degree of statistical reliability for all measurements in a series of counting measurements (see Chapter 9). When the PSC mode is used, a method must be available to determine the elapsed time for each counting measurement (e.g., a visual display or printout of elapsed counting time) so that counting rates for each measurement can be determined (preset counts/elapsed time).

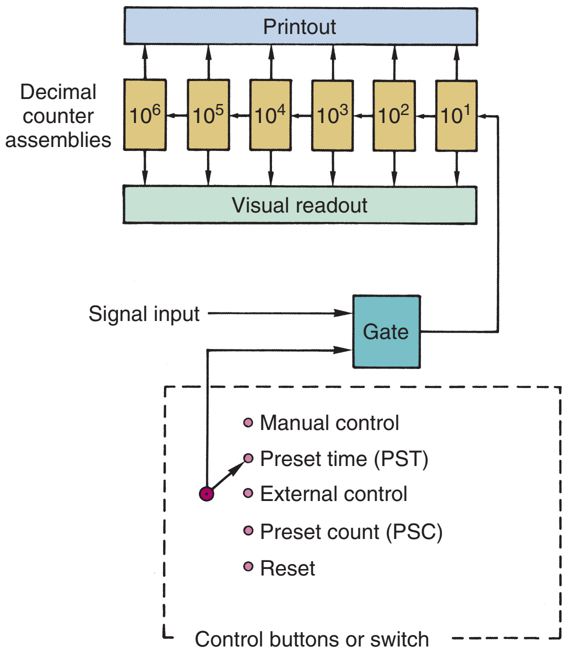


FIGURE 8-12 Schematic representation of components and controls for a scaler-timer.

External control of the scaler gate may be provided by an external timer or a sample-changer assembly. *Manual control* permits the operator to start and stop the counting interval by depressing front-panel "start" and "stop" buttons. In computer-controlled counters, all these parameters are controlled by keyboard entry and appropriate interface software.

The maximum counting rate capability depends on the minimum time separation required between two pulses for the scaler to record them as separate events. A 20-MHz scaler (2×10^7 counts/sec) can separate pulses that are spaced by 50 nsec, or 5×10^{-8} sec apart (2×10^7 counts/sec is equivalent to 1 count/5×10^{-8} sec). Most modern scalers are capable of 20- to 50-MHz counting rates, which means they can count at rates of several hundred thousand counts per second with losses of 1% or less caused by pulse overlap (see Chapter 11, Section C). Because pulse resolving times of most radiation detectors and their associated preamplifiers and amplifiers are on the order of 1 µsec, the counting rate limits of modern scalers are rarely of practical concern.

2. Analog Rate Meters

An *analog rate meter* is used to determine the average number of events (e.g., SCA output pulses) occurring per unit of time. The average is determined continuously, rather than during discrete counting intervals, as would be the case with a scaler-timer. The output of a rate meter is a continuously varying voltage level proportional to the average rate at which pulses are received at the rate meter input. The output voltage can be displayed on a front-panel meter or interfaced through a continuously sampling ADC to a personal computer. Rate meters are commonly used in radiation monitors (see Figs. 7-3 and 7-11).

Figure 8-13 shows the basic components of an analog rate meter. Input pulses pass through a pulse shaper, which shapes them to a constant amplitude and width. Each shaped pulse then causes a fixed amount of charge, Q, to be deposited on the capacitor C. The rate at which the charge discharges through the resistor R is determined by the product R × C, which is called the *rate meter time constant* τ.

Suppose that input pulses arrive at an average rate $\bar{n}$ pulses per second. The capacitor discharge then produces an average current I through the resistor R given by

$$I = \bar{n}Q \tag{8-6}$$

By Ohm's law, this causes an average voltage

$$V = \bar{n}Q\mathrm{R} \tag{8-7}$$

to appear at the input to amplifier A. If the amplification factor of this amplifier is k, the average output voltage V_o is given by

$$V_o = k\bar{n}Q\mathrm{R} \tag{8-8}$$

Thus if k, Q, and R are constant factors for a given measurement, average output voltage V_o is proportional to average input counting rate $\bar{n}$.

The output voltage V_o can be used to drive a meter to read the average counting rate. The calibration usually is performed by adjusting the amplifier gain factor k. This factor is adjusted to select different full-scale ranges for the readout device, for example, 0-1000 cpm, 0-10,000 cpm, and so on.

A rate meter that follows the relationship described by Equation 8-8 is called a *linear* rate meter. For some applications it is desirable to have a logarithmic relationship:

$$V_o = k\log(\bar{n}Q\mathrm{R}) \tag{8-9}$$

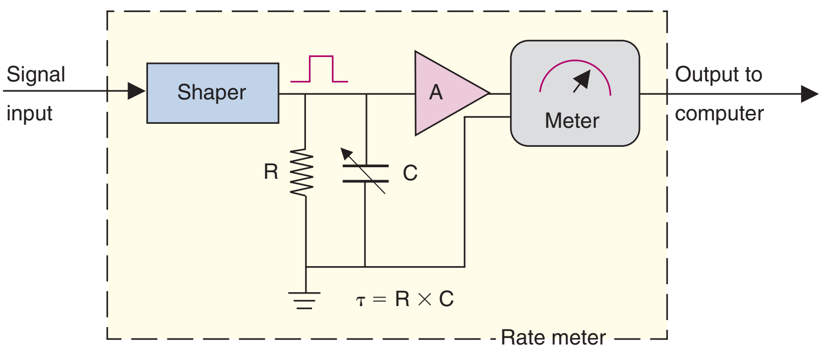


FIGURE 8-13 Schematic representation of an analog rate meter. Adjustable capacitor C provides variable *rate meter time constant*, τ.

The logarithmic conversion usually is performed by a logarithmic amplifier. *Logarithmic rate meters* have the advantage of a very wide range of counting rate measurement, typically 4 or 5 decades, without the need to change range settings as with a linear rate meter; however, it is more difficult to discern small changes in counting rate with a logarithmic rate meter.

The voltage relationships described by Equations 8-8 and 8-9 apply to *average* values only. When the input pulse rate changes, the rate meter output voltage does not respond instantaneously but responds during a period determined by the rate meter time constant τ. Figure 8-14 illustrates the response characteristic of a linear rate meter. The relationship between indicated counting rate R_i and the new average counting $\bar{R}_a$, following a change occurring at time $t = 0$ from a previous average value, $\bar{R}_0$, is given by

$$R_i = \bar{R}_a - (\bar{R}_a - \bar{R}_0)e^{-t/\tau} \qquad (8\text{-}10)$$

The rate meter reading (or output voltage) approaches its new average value exponentially with time *t*. Typically, three to five time constants are needed to reach a new stable value.

The rate meter time constant is selected by a front-panel switch (usually by adjusting the capacitor value C) and may range from 100ths of a second to 10s of seconds. Figure 8-14 shows that a rate meter actually provides a distorted representation of counting rate versus time (rounded edges and delayed response). This distortion can be minimized by choosing a very short time constant (Fig. 8-14 A). A long time constant has the advantage of smoothing out statistical fluctuations in counting rate, but it produces a more distorted representation of changes in counting rates (Fig. 8-14B).

F. COINCIDENCE UNITS

Coincidence units are logic units that produce a pulse only if two or more input pulses occur within a particular coincidence time window. One method for doing this is to sum the input pulses and pass them through a discriminator that is set just below the amplitude that would be seen if two or more pulses occurred simultaneously. As shown in Figure 8-15, the unit supplies an output pulse only when two or more pulses overlap in time and the discriminator threshold is exceeded. The *coincidence timing window* is the maximum time interval between two pulses for them to be counted as being in coincidence. In this illustration, this is twice the width of the input pulses (2τ).

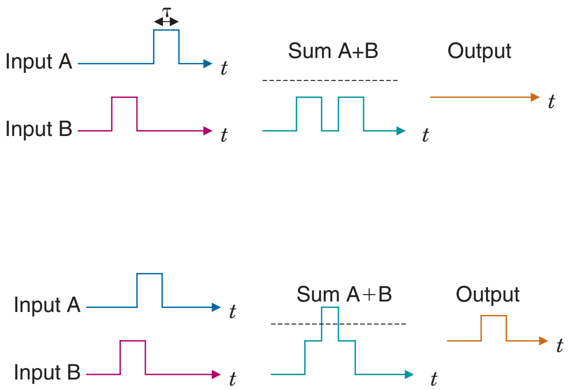


FIGURE 8-15 Principles of a coincidence unit. The signals from the inputs are combined and passed through a discriminator set just below the threshold required for simultaneous pulses on the two inputs. In this example, the coincidence window is approximately twice the width of the input pulses (2τ).

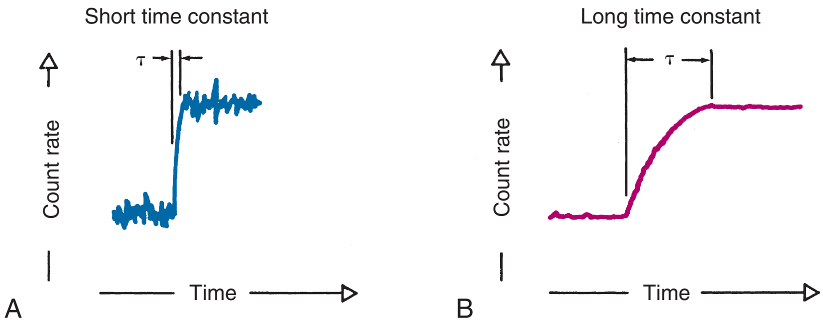


FIGURE 8-14 Rate meter response to a sudden change in counting rate for different rate meter time constants. A short time constant (*A*) reflects the change more accurately, but a long time constant (*B*) provides better averaging of statistical noise fluctuations.

Coincidence units often have up to four inputs and permit selection of two-way, three-way, and four-way coincidences between the input pulses. Of most interest in nuclear medicine is the use of coincidence units to identify the two-way coincidence events resulting from the detection of the annihilation photons from positron-emitting radionuclides (Chapter 18, Section A.1). In practice, most positron imaging systems record and compare the time for each detected event using digital electronics, rather than using the analog coincidence units described previously. In this case, the coincidence timing window is just the maximum time difference allowed between two events for them still to be considered in coincidence. Another use of coincidence units is to minimize background in liquid scintillation counting (Chapter 12, Section C).

G. HIGH-VOLTAGE POWER SUPPLIES

The high-voltage (HV) power supply provides the charge collection voltage for semiconductor, gas proportional, and GM detectors and the accelerating voltage for electron multiplication in the PM tubes used with scintillation detectors such as NaI(Tl) and liquid scintillators. The HV power supply converts the alternating current voltage provided by the line source into a constant or direct current (DC) voltage.

Whereas variation of the HV has little effect on the output pulse amplitude with semiconductor and GM detectors, changes in the HV with gas proportional or scintillation detectors strongly affect their output pulse amplitude. For example, a 1% change in the HV on a scintillation detector PM tube can change the output pulse amplitude by 10% or more because the HV on the PM tube (and on gas proportional counters) determines the multiplication factor for the number of electrons caused by an ionization event in those detectors (Chapter 7, Section C.2).

Instabilities in HV power supplies can arise from a number of factors, such as temperature changes, variations in line voltage, and the amount of current drawn by the detector (commonly referred to as the *output load*). The output can also drift over time. In a well-regulated HV power supply suitable for scintillation detectors, drifting of the output with time and temperature are more important than the effects of line voltage and current loads (unless maximum current ratings are exceeded); however, the former problems are still relatively small, because modern HV supplies are very stable for long periods and over wide temperature ranges.

The output current rating of the HV power supply must be sufficient for the particular detector system. Most scintillation detectors draw about 1 mA of current, for which the 0- to 10-mA rating of most commercial HV supplies is adequate. If the current load is inadvertently increased above this limit, it will affect the stability and may even damage the HV supply. Thus the current requirements of the detector or detectors should be within the specified limits for the HV supply. The current requirements need to be specified at the intended operating voltage of the detector, because the current load drawn by the detector will increase with the applied voltage. Most commercial HV supplies have an overload protection circuit that will shut off the unit if the recommended current load is exceeded.

Superimposed on the DC output of the HV supply is a time-varying component, usually of relatively small amplitude, referred to as "ripple." The amplitude of ripple ranges from 10 to 100 mV in most commercial units. Ripple in the HV supply can be a serious problem with high-resolution semiconductor detectors, because it produces noise in the detector output and reduces the energy resolution of the detector. HV supplies used in conjunction with high-resolution semiconductors usually have a ripple of less than 10 mV.

H. NUCLEAR INSTRUMENT MODULES

Most of the counting and imaging instruments used in nuclear medicine are dedicated to specific and well-defined tasks. Usually, they are designed as self-contained "hardwired" units, with no capability for interchanging components, such as amplifiers, SCAs, or scalers, between different instruments. Although these integrated circuits generally result in an efficiently designed and attractively packaged instrument, there are some applications, especially in research, for which interchangeability of components is highly desirable. For example, most scalers, timers, and rate meters can be used with any detector system, but different detectors may require different amplifiers, and different types of PHAs may be desired for different pulse-timing requirements.

Flexibility and interchangeability of components are provided by the *nuclear* *instrument module* (NIM). Individual NIM components (such as scalers and amplifiers) slide into slots in a master "bin" from which they draw their operating power. They have standard input and output signals and are interconnectable with standard cables and connectors.

A NIM system generally is more expensive than a dedicated system with the same capabilities; however, it has the advantage that it can be upgraded or applied to different radiation detectors and counting problems by replacement of individual components rather than replacing the entire unit. A wide variety of component types and performance specifications are available in the NIM standard.

I. OSCILLOSCOPES

The oscilloscope is an instrument that displays as a function of time the amplitude (voltage) and frequency of signals. It is used for examining the pulses from the pulse-processing units described in the previous sections of this chapter and for testing, calibrating, and repairing electronic equipment in nuclear medicine.

1. Cathode Ray Tube

Analog oscilloscopes, as well as older nuclear medicine systems (gamma cameras, liquid scintillation counters, well counters, and MCAs) typically use a cathode ray tube (CRT) display. The CRT is an evacuated tube containing the basic components shown in Figure 8-16. The *electron gun* provides a focused source of electrons. Most CRTs use a hot, or thermionic emission, cathode. Electrons are boiled off the cathode by heating it with an electric current. The *control grid* is a cap that fits over the cathode. The electrons pass through a small hole in its center. A negative potential on the grid can be varied to control the number of electrons that are allowed to pass. The *first anode,* or *accelerating anode,* is similar in shape to the grid except that its orientation is reversed. The flat end contains a small hole through which the electrons pass. It has a high positive potential that attracts the electrons and accelerates them to high velocities. Most of the electrons actually strike the front face of the first anode, but a small percentage pass through the opening and are accelerated down the CRT tube as a narrow beam.

The *second anode,* or *focusing anode,* further shapes the electron beam by focusing it to a sharp point where it strikes the phosphor-coated screen. A negative potential on the second anode is used to both compress and focus the beam of electrons. The diameter of the electron beam striking the phosphor screen is usually around 0.1 mm.

Deflection plates are used to move the electron beam across the screen. Electrostatic deflection employs two sets of plates mounted at right angles to each other. Voltages are applied to one pair to exert a force on the electron beam in the vertical direction and on the other pair for the horizontal direction on the display screen. The amount of deflection is proportional to the voltage applied to the deflection plates.

The *display screen* is a glass screen having an inside surface coated with a phosphorescent material. The high-velocity electrons striking the phosphor cause it to give off phosphorescent light. The brightness of the phosphorescent light depends on the intensity and energy of the electron beam. The lifetime of the light emission from the phosphor is

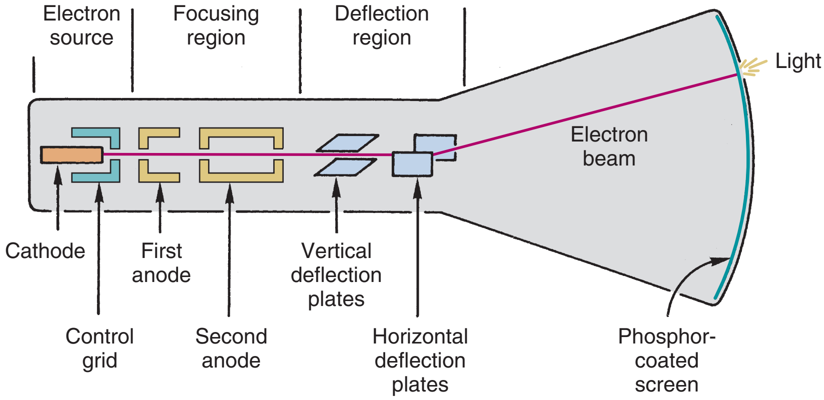


FIGURE 8-16 Basic components of a cathode ray tube.

referred to as the *persistence time* and is typically 0.5 msec on an oscilloscope display.

2. Analog Oscilloscope

A typical analog oscilloscope consists of a CRT, a signal amplifier for the vertical deflection plate of the CRT, and a time-sweep generator. An amplifier is provided so that small voltage inputs can be amplified and applied to the vertical deflection plate to display the amplitude of the input signals. The time-sweep generator is connected to the horizontal deflection plates of the CRT to sweep the electron beam across the screen at a constant speed and repetition rate. The horizontal sweep rate usually can be varied from nanoseconds (10^{-9} sec) to seconds per centimeter by a calibrated selector switch on the front panel of the oscilloscope. Thus the oscilloscope provides a visual display of time-varying electrical signals.

3. Digital Oscilloscope

Most modern oscilloscopes are digital, employing fast ADCs that digitize the amplified waveforms prior to display, and some form of microprocessor that allows pulses to be analyzed and manipulated. The CRT screen is typically replaced with a flat-panel liquid crystal display. Digital oscilloscopes have the advantage that pulses can be stored in computer memory for further analysis and are ideal for studying repetitive, regular pulses. The disadvantage of using a digital oscilloscope to look at the pulses from γ-ray detectors is that individual pulses generally are of a different amplitude (reflecting differing energies deposited in the detector), and that they arrive randomly in time. A digital oscilloscope shows only one pulse at a time. Some digital oscilloscopes now have a "persistence" function (essentially software or hardware that mimics the response of a phosphorescent screen), which allows many pulses to be viewed simultaneously, with appropriate intensity where pulses overlap. This allows the range of pulse amplitudes and shapes to be appreciated easily in a single glance and gives the digital oscilloscope the feel of an older analog oscilloscope with a fairly long (10^{-1} to 1 sec) persistence phosphor.

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