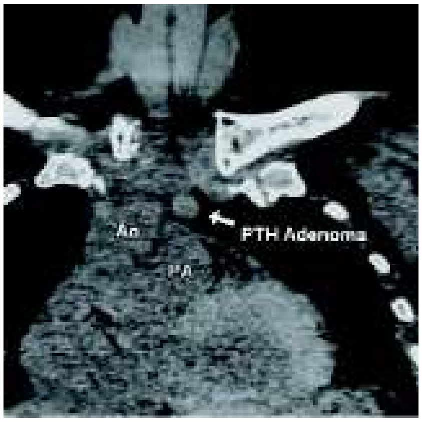
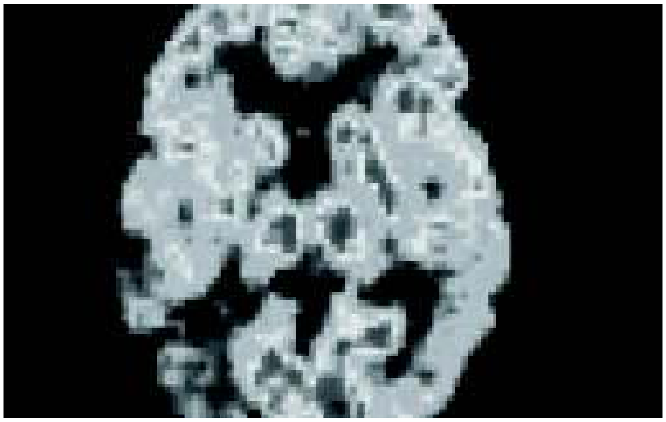
CHAPTER 1

Gas-Filled Detectors





Learning Outcomes

1. Diagram a gas-filled detector and describe how it detects radiation.
2. Draw the voltage response curve for gas-filled detectors and describe each region.
3. Distinguish between current mode and pulse mode, and discuss the consequences of each in common gas-filled detectors.
4. Describe the proper use of a dose calibrator, including the importance of the isotope selector buttons.
5. Distinguish between an ionization survey meter and a Geiger counter, in regard to their operation and appropriate use.
6. Outline the process of radiation detection in a Geiger counter, including the time constant and the need for recovery of the gas chamber.
7. List the recommended quality control tests for gas-filled detectors and their frequencies.
8. Discuss the limitations of gas-filled detectors.

Introduction

Radiation interacts with atoms and molecules, resulting in ionization, which creates ion pairs. An *ion pair* consists of a free electron and the remaining ionized atom or molecule, now positively charged. Each ion pair requires a finite amount of radiation energy, so the number of electrons created is related to the amount of radiation or radioactivity present. These electrons can be caused to move by the application of an electrical field. Thus, the most direct way to detect ionizing radiation is to use electronic equipment to measure the number of electrons created by radiation interactions. The simplest radiation detectors that operate on this principle are called gas-filled detectors, because the ion pairs are created in a chamber filled with gas. Within this class of radiation detectors, we discuss dose calibrators, ionization survey meters, and Geiger counters. Several other gas-filled detectors make useful radiation detectors, but those discussed here are those in common use in nuclear medicine.

Basic Operation

A simple model with only two essential parts—a chamber filled with a gas (hence the term *gas-filled detector*) and a basic electric circuit—is used to illustrate the operation of these instruments (**Figure 1-1**). The structure of the chamber allows it to function as a capacitor; the reader is referred to Appendix B for more information about the electronics of radiation detection instruments. The chamber consists of a positively charged central wire (the *anode*) surrounded by a negatively charged metal tube (the *cathode*). The anode and cathode are separated by a gas and are connected to an external power source. The power source keeps the anode and cathode charged with

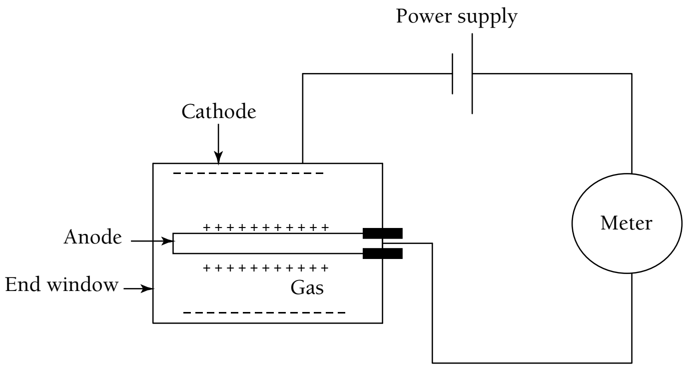


Figure 1-1 Block diagram of a gas-filled detector. The cathode usually forms the outside of the detector, and the anode is an internal plate or wire. The detector has a power source that keeps the cathode and anode charged with negative and positive charge, respectively. The anode and cathode thus form a capacitor, as described in Appendix B. The meter measures either voltage or current, depending on the particulars of the detector design.

as much positive and negative charge, respectively, as their size and the power source's voltage allow. The meter measures the flow of electricity that occurs as a result of neutralization of charge at the anode and cathode.

In the absence of radiation interactions, the gas between the anode and cathode acts as an insulator, and there is no movement of electrical charge. When radiation (gamma rays, x-rays, or charged particles with energy greater than 10 electron volts [eV]) passes through the gas, it ionizes one or more gas molecules, producing free electrons and positive ions. (A brief review of atomic structure and radiation interactions is found in Appendix A.) The average amount of energy required to cause an ionization depends on the type of gas used in the chamber, but is generally between 20 and 45 eV per ion pair. The free electrons and positive ions drift toward the anode and cathode, respectively. Electrons move much faster than the positive ions they leave behind, so we can discuss the collection of electrons at the anode, ignoring for the moment the positive ions created by the radiation interactions. As they move, both electrons and positive ions undergo ionization and excitation interactions with other gas molecules, producing many low-energy *tertiary electrons*. Electrons that reach the anode neutralize some of the positive charge, thus causing electricity to flow through the connecting circuitry to restore the capacitor to its original state. We can measure this neutralization as either current (current mode) or voltage (pulse mode), as discussed in a later section.

The number of electrons measured will depend on several factors, including the number of charged particles and/or photons being measured (i.e., the strength of the radiation source or field); the energy of the radiation; the geometric configuration of the detector; the composition of the gas in the chamber; and the volume, pressure, and temperature of the gas. But a major determinant is the applied voltage between the anode and cathode. Because the electrical potential difference between the anode and cathode provides the driving force behind the movement of the electrons, its magnitude determines how many electrons reach the anode and cathode and what happens to them along the way. For now, let us leave aside the effects of energy, geometry, and gas composition and look at the effect of changing the voltage between the anode and cathode.

Voltage Response Curve

The applied voltage between the anode and cathode is the most important determinant of how many electrons are measured. **Figure 1-2** shows a typical voltage response curve. Its shape can be understood by looking at what is happening in each of the six regions.

Recombination Region

If the applied voltage is quite low, the electrons are moving so slowly that some recombine with other ionized gas molecules and do not reach the anode and cathode, resulting in an incomplete collection of ions. In this region, as the applied voltage is increased, more electrons reach the anode and the measured signal gets larger. There are no usable detectors that operate in this region of the voltage response curve.

Ionization Region (Saturation Region)

As the applied voltage is increased, the system reaches a point at which all electrons are being collected, with no recombination. The *saturation voltage* is a voltage sufficient for this condition of saturation to be reached. There is a

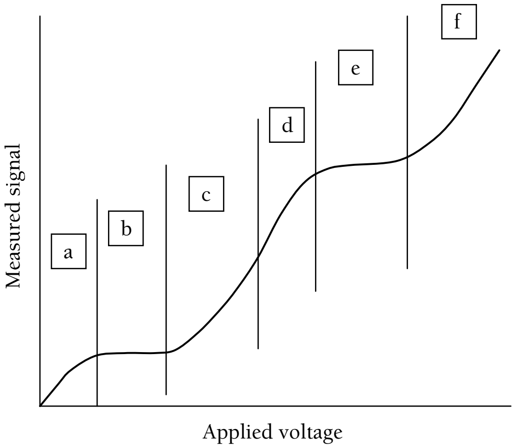


Figure 1-2 Voltage response curve for a gas-filled detector. The regions are (a) recombination, (b) ionization, (c) proportional, (d) limited proportional, (e) Geiger–Müller, and (f) continuous discharge. The shape of the curve is explained in the text.

wide range over which the response is flat, such that even if the voltage fluctuates, the same number of electrons will be collected. The magnitude of the signal is thus proportional to the rate at which photons or charged particles are interacting in the detector. The dose calibrator and ionization survey meter operate in this region.

Proportional Region

If we increase the applied voltage above the saturation voltage, the tertiary electrons are accelerated. They may gain enough kinetic energy to exceed the 10-eV threshold, meaning that they will cause additional secondary ionizations through collisions with other gas molecules. This produces a cascade of electrons called a *Townsend avalanche*. An increase in the applied voltage above the saturation voltage thus produces a signal that is larger than, but still proportional to, the number of ion pairs produced by the radiation (a phenomenon known as *gas amplification*). Gas-filled detectors that operate in this region, called *proportional counters*, are primarily used to detect and distinguish between alpha and beta particles and to identify radionuclides based on these decay products. Proportional counters are quite useful in many physics applications but are not commonly employed in nuclear medicine.

Region of Limited Proportionality

It is in this region that we must begin to consider the fate of the positive ions created by the interaction of radiation with gas molecules. These ions are much larger than electrons and hence drift slowly toward the cathode. In this voltage range, each interaction produces a cloud of positive ions that takes a finite amount of time to disperse. The electric field experienced by the electrons is momentarily decreased, because they are being pulled in two directions—toward the anode and toward the clouds of positive ions. This causes a decrease in the amount of gas amplification. Thus the voltage response curve no longer changes linearly with increasing voltage. This region is not useful for radiation detection.

Geiger–Müller Region

At very high voltages, the gas amplification effect is maximized, so that each electron created produces many ionizations as it races toward the anode. In addition, the moving electrons raise many other gas molecules to excited states via collision interactions, from which they may deexcite by emission of ultraviolet (UV) photons. These UV photons can interact with other gas molecules via photoelectric interactions, producing more free electrons, which in turn are accelerated toward the anode and cause more ionizations and excitations. Thus, each radiation event produces a large avalanche of ions called a *Geiger discharge* throughout the chamber (**Figure 1-3**). The circuit in this case produces a large electrical pulse in response to each radiation event, regardless of the applied voltage (within the Geiger–Müller range) or the energy of the radiation. The pulse size is essentially the same for all radiation events, no matter the type of radiation or the amount of energy transfer. The Geiger counter, a commonly used radiation detector, operates in this region.

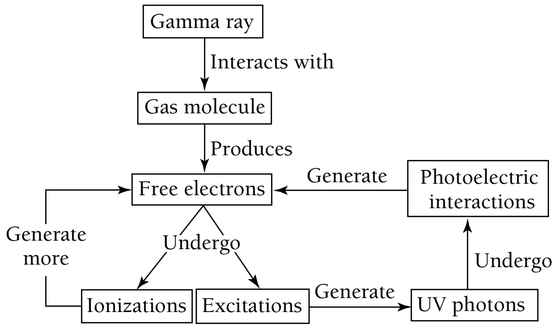


Figure 1-3 Concept map illustrating the Geiger discharge. Each electron created in the chamber interacts with gas molecules via ionization interactions (which create more electrons, the left-hand branch in the diagram) or excitation (which produces UV photons that may be energetic enough to cause more ionizations, the right-hand branch in the diagram). This cycle recurs many, many times. Thus, in a gas-filled detector operating in the Geiger–Müller region, each detected gamma ray creates a large electrical signal.

Continuous Discharge Region

An increase in the voltage above the Geiger–Müller voltage range causes spontaneous ionizations in the detector in the absence of radiation. There are no useful radiation detectors here; operation of a radiation detector in the continuous discharge region can result in permanent damage to the detector.

Current vs Pulse Mode

The electrons that are created in the gas chamber are collected at the anode. The number of electrons collected is correlated to the amount of radioactivity or the strength of the radiation field. This measurement is accomplished in one of two ways. *Current mode* measures the number of electrons per second required to keep the anode and cathode charged. Detectors that operate in current mode are connected to a power supply that constantly strives to keep the anode and cathode charged to their fullest capacity. As electrons produced by radiation interactions neutralize some of the charge on the capacitor, electrons flow from the power source to restore the charge; this electron flow constitutes the measured current. The measurement is therefore based on the time-averaged number of ionizations occurring per second. Current-mode detectors generally operate at high-voltage values that place them in the ionization region.

Because it is an average, an instrument operated in current mode will reach a steady reading over time, as long as the source strength and source-detector distance remain the same. When the radiation level is changing, the reading from a current-mode detector will change based on its averaging time. Some systems allow for the averaging time to take on different values; others do not. Current mode requires a relatively large amount of radiation (many events per second) to produce a precise reading, and even then it generates current in the picoampere (1 pA = 10^{-12} ampere [A]) range. At low levels of radiation, current-mode detectors are subject to statistical fluctuations and interference from leakage currents (movement of electrons through the circuitry in the absence of radiation).

In *pulse mode*, the electrons created by each radiation interaction are treated as a group, and the pulse they create is measured as a single entity. The size of the pulse (either its height or the area under the signal-vs-time function, integrated over time) represents the total charge deposited in the detector by a single radiation interaction. Restoring the electrical potential between anode and cathode still requires an electric current, as in the current-mode detector, but in practice it is easier to measure voltage changes than current changes. Therefore, an RC circuit (a resistor and a capacitor in parallel) is introduced into the circuitry of most pulse-mode detectors, to convert current to voltage (see Appendix B for more details). This also allows the shaping of the pulse, which is necessary for pulse separation and counting. The detector thus reports the number of pulses registered per second, which in turn depends on the amount of radioactivity or the strength of the radiation field.

The underlying assumption of pulse mode is that radiation interactions are separated by enough time that the system can register each one individually. Pulse-mode operation therefore requires a lower rate of radiation interactions in the detector than current mode does. As the interaction rate increases, the readings obtained from a pulse-mode detector will become less accurate, primarily due to dead time. In addition, instruments operating in pulse mode will demonstrate more of the variability characteristic of low-level radiation detection, such that the reading will tend to bounce around, depending on the source intensity and the particular settings used.

Two of the radiation detection instruments discussed in this chapter, the dose calibrator and the ionization survey meter, operate in current mode. The third, the Geiger counter, operates in pulse mode. Most other nuclear medicine equipment, including semiconductor detectors, scintillation detectors, and all forms of imaging systems, also operate in pulse mode. These instruments differ from gas-filled detectors in that the amplitude of each pulse represents the energy deposited in the detector by an individual gamma ray. The ability to determine energy gives these detectors an edge over gas-filled detectors for applications in which energy discrimination is needed.

Dose Calibrator

A *dose calibrator* is used to measure the activity of radionuclide samples. It is calibrated in units of Curies (Ci) and/or Becquerels (Bq). It is truly a workhorse of nuclear medicine, because most departments use a dose calibrator to check every radiopharmaceutical dose that is received or dispensed. A good understanding of how a dose calibrator works, and what it can and cannot do, is therefore vital to the proper care of patients.

Design Features

The basic design of a dose calibrator is shown in **Figure 1-4**, and **Figure 1-5** shows a commercially available model. It operates in the ionization region of the voltage response graph, meaning that all of the primary electrons created in the chamber of the dose calibrator reach the anode, without gas amplification. A dose calibrator is a current-mode instrument: the number of electrons reaching the anode per second is integrated over time, so that it reaches a steady reading over a second or two.

The anode and cathode are found inside the chamber of the dose calibrator. The voltage supply is about 150 volts (V). Typically, the chamber contains either air or argon gas under high pressure (12 or more atmospheres [atm]), which increases the likelihood of gamma ray interactions with the gas. A *dipper* (a gravy-ladle-shaped device fabricated out of Plexiglas®) is used to lower the source container into the cylindrical space that is surrounded by the gas chamber. The outside of the chamber is shielded by a lead cylinder both to prevent external radiation sources from contributing to the measurement and to shield the surrounding area from the

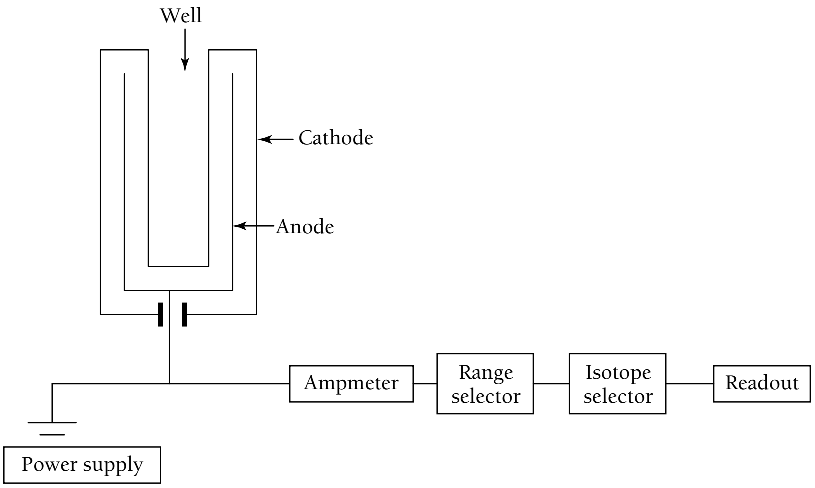


Figure 1-4 Block diagram of a dose calibrator. In addition to the components shown, most dose calibrators sold today have a microprocessor unit that does decay mathematics, saving the user from many calculations. The dose calibrator may also be tied to a computer for tracking of dosage administrations, quality control data entry, and so on.

Figure 1-5 A commercial dose calibrator. One can see the shield of the ionization chamber with the dipper handle at the top, as well as the electronic readout module. Photo courtesy of Capintec, Inc.

source being measured. This shield causes some gamma rays to backscatter into the gas chamber, increasing the ionization current when it is present compared to when it is absent. The dose calibrator is calibrated with its shield, and readings are accurate only if it remains in place.

Isotope Selector Buttons

The current that is produced by a radioactive source in the dose calibrator is proportional to both the amount of radioactivity (the desired information) and the energy of the photons, which is dependent on the radionuclide being measured. The dose calibrator by itself cannot distinguish between photons of different energies, and therefore it cannot discriminate between different radionuclides. The operator must do this job using *isotope selector buttons*, which multiply the measured current by a current→activity conversion factor that is specific for each radionuclide. The values of these conversion factors are determined during the initial calibration of the dose calibrator. In older, electromechanical dose calibrators, the values were hardwired into the electronics of the dose calibrator (usually through incorporation of resistors), whereas in newer microprocessor-driven machines they are programmed into the readout as multiplication factors. In either case, it is important to recognize that the dose calibrator will not give an accurate measurement if an incorrect isotope selector button is chosen.

At the factory, a calibration curve is determined using a series of long-lived radionuclide sources, whose activities are traceable to standards at the National Institute of Standards and Testing (NIST) and are thus known exactly. The calibration curve is in turn used to determine conversion factors for the short-lived radionuclides used in nuclear medicine. It is these values that are programmed into the isotope selector buttons. A manual mode allows the user to enter conversion factors not available as preset buttons; the manufacturer usually supplies a table of conversion factor values for a wide variety of radionuclides in addition to those with preset buttons. Once established, the conversion factor for a given isotope selector button is applied to the current measured when a radioactive source is placed in the well.

Sample Calculation 1-1 Isotope-Specific Conversion Factors

The following conversion factors apply to a specific dose calibrator:

$$\text{Tc-99m}: \frac{0.5\ \text{pA}}{\text{mCi}}.$$

$$\text{I-131}: \frac{0.2\ \text{pA}}{\text{mCi}}.$$

A syringe containing a radionuclide is put into the dose calibrator. It generates a current of 2 pA. Calculate the activity if the Tc-99m button is chosen and if the I-131 button is chosen.

$$\text{Tc-99m}: \quad \frac{2\ \text{pA}}{0.5\ \text{pA/mCi}} = 4\ \text{mCi}.$$

$$\text{I-131}: \quad \frac{2\ \text{pA}}{0.2\ \text{pA/mCi}} = 10\ \text{mCi}.$$

The dose calibrator cannot tell which value is correct. It will faithfully give a value for the activity of a sample, based on whichever isotope selector button is engaged. It is incumbent on the operator to make sure that the correct button is chosen.

Operation

The use of a dose calibrator is quite elementary: with the correct isotope selector button depressed, one puts a vial or syringe of radioactive material into the dipper, which is lowered into the well. The number of ionizations created in the gas chamber per second is measured and converted by the isotope selector button to a readout in Ci or Bq. Dose calibrators can measure quantities down to about 20 μCi (740 kBq) to within ±5% (1); below this level, they are less accurate and may take a longer time to reach a steady value. A sodium iodide scintillation detector should be used if accuracy is important at very low activities.

Often nuclear medicine doses are assayed at a different time than they are administered. The dose calibrator reading must then be decay-corrected to the time of administration. Many modern dose calibrators incorporate a clock and calculate radioactive decay internally, thus eliminating the requirement for a separate calculation to determine present activity based on a desired future dosage. These dose calibrators can also keep track of elution vial activities and radiopharmaceutical kit activity concentrations. Many dose calibrator vendors offer computers, printers, and data ports for communication with other devices.

Dose calibrators have an electronic means of setting the background to zero when the source chamber is empty. This process should be engaged at least once per day and preferably several times each day. However, the zero point will be incorrect if there is contamination inside the well. Dose calibrators have a removable plastic liner to protect the inside of the well. If either the liner or the dipper becomes contaminated and the background-setting process is engaged, the machine will rezero to a different level, accounting for the elevated background reading. As the contamination decays, the reading of the empty dose calibrator becomes more and more negative. Dippers and liners should be cleaned if contamination is suspected; it is recommended to have a spare dipper and liner for such occasions.

As was stated previously, dose calibrators cannot distinguish between photons of different energies. The operator can, however, estimate the activity of a radionuclide with high-energy gamma rays in the presence of a radionuclide with low-energy gamma rays through the use of a lead vial shield, as is routinely done in measuring the Mo-99 contents of a generator elution. The *moly shield* is a lead vial shield or "pig" of about 0.5 cm thickness. This is plenty of lead to absorb the great majority of Tc-99m gamma rays (140 keV), but about 50% of Mo-99 gamma rays (750–800 keV) pass through the shield and are measured by the dose calibrator. A correction factor is incorporated into the "Moly assay" selector button that accounts for the partial absorption of Mo-99 gamma rays in the moly shield. The correction factor may also include the 12-hour decay factors for Tc-99m and Mo-99, corresponding to the eluate's expiration time. Using the moly shield and the correction factor, μCi (kBq) amounts of Mo-99 can be measured in the presence of Ci (GBq) amounts of Tc-99m.

Dose calibrators are not able to measure the activity of most pure beta-emitting radionuclides directly, because the beta particles cannot penetrate the liner and wall of the chamber to enter the gas space. However, most commercially available dose calibrators have a correction table to allow estimation of the assay of beta-emitting radionuclides based on the Bremsstrahlung radiation emissions they generate. Such readings are still subject to inaccuracies due to the container the radionuclide is in (see the information on geometry testing in Quality Control). One way to accurately assay a pure beta-emitting radiopharmaceutical dosage is as follows (**Table 1-1**): Prior to administration, place the syringe or vial into the dose calibrator, and dial in the conversion factor for the radionuclide. Then manually adjust the conversion factor so that the measured activity matches the activity calculated from the calibration data. (With some radionuclides, the Bremsstrahlung radiation is so weak that the reading cannot be adjusted to the calculated activity. In such a case, adjust the manual setting so that the reading is some fraction [e.g., 10%] of the calculated value.) After drawing or administering the dose, remeasure the syringe or vial on the same setting and in the same container. The administered amount is equal to the difference between the two measurements (multiplied by the inverse of the correction fraction if one was needed).

Table 1-1

Example Measurement of a Pure Beta-Emitting Radionuclide

Sr-89 strontium chloride assay	
Activity based on calibration data	4.11 mCi
Adjust dose calibrator to read calculated activity	4.11 mCi
Draw dose	
Measure vial after drawing dose (add water to restore original volume)	0.23 mCi
Dosage withdrawn from vial	3.88 mCi

Ionization Survey Meter

These gas-filled detectors are primarily used to measure exposure rates from radiation fields. (The colloquial name for such detectors, "Cutie Pie," derives from the symbols $Qd\pi$, which are included in the mathematical formula for the detector's sensitivity.) They may also be called *ion chambers* or *exposure rate meters*. An example of an ionization survey meter is shown in **Figure 1-6**.

Design Features

Most commercially available ionization survey meters are filled with air and are battery driven (50–500 V), operating in the ionization region and in current mode. A range setting or scale knob allows radiation exposure rates over several orders of magnitude to be measured. Ionization survey meters may read in *rate mode*, the time-averaged radiation exposure rate in milliroentgens per hour (mR/hr), or in *integrate mode*, giving the total accumulated radiation exposure in mR over a period of time. (A *Roentgen* [R] is an

Figure 1-6 Ionization survey meter. Note the single-unit construction, which distinguishes an ionization survey meter from most Geiger counters. Photo courtesy of Biodex Medical Systems, Inc.

amount of radiation that produces 1 electrostatic unit of charge [about 2 billion ion pairs] in 1 cm^3 of air. It is commonly used to describe the strength of a radiation field.)

An ionization survey meter generally has a *thin entrance window* made of a thin layer of mica, mylar, or other low-atomic-number material, that is protected by a sliding or removable shield. If the measurement is to include only photon radiation, the shield is left in place, covering the thin entrance window, so that it absorbs any particulate radiations (i.e., electrons, beta particles, and/or alpha particles) and low-energy photons. If the measurement is to include particulate radiation or low-energy gamma rays, the shield is moved aside to allow these radiation types to cross through the thin entrance window. The readings with and without the shield can be compared to determine the relative amounts of penetrating and nonpenetrating radiation.

Uses

Ionization survey meters are often utilized interchangeably with Geiger counters, but there are important differences that the operator should understand. First, ionization survey meters require a higher radiation flux than do Geiger counters to produce a precise reading. They generally read accurately down to about 1 mR/hr (2). They are therefore applicable to situations such as monitoring radiation levels of patients receiving radionuclides or radioactive implants for therapy, but are not appropriate for detecting radioactive contamination. Second, ionization survey meters have a relatively constant response over a range of gamma ray energies between about 20 and 1,300 keV. They are thus suitable for measuring ambient radiation levels involving mixed photon energies.

Finally, the measured exposure accurately reflects the ionization density in air and can therefore be used as a starting point for some calculations of radiation-absorbed dose for dosimetry purposes. A number called the *work function* estimates the energy required to create one ion pair in the fill gas of the meter. This number can be multiplied by the meter's reading (converted from mR to ion pairs) to calculate the total energy deposited in the gas chamber. This value in turn can be converted to an equivalent value for water (which for radiation absorption purposes is similar to tissue). Using this type of procedure, one can, for example, convert the ionization survey meter "integrate" reading from a nurse's visit with a radioactive patient into an absorbed-dose value for the nurse.

Geiger–Müller Survey Meter

The Geiger–Müller survey meter or Geiger counter is another workhorse of health physics in general and of nuclear medicine departments in particular. It is also one of the oldest radiation detectors, having been invented by Hans Geiger in 1908–1912 and improved by Walther Müller in 1928. It operates in the Geiger–Müller region of the voltage response curve, at 400 to 2,000 V. The electronic signal in a Geiger counter is more complex than in detectors operating in the ionization region and deserves additional explanation.

Operation

In the Geiger–Müller region, each electron produced in an ionization interaction is given a large amount of kinetic energy, so that it causes additional ionizations (a *Townsend avalanche*) and excitations of gas molecules as it is pulled toward the anode. Gas molecules raised to an excited state may produce ultraviolet-wavelength photons, which in turn may be absorbed in photoelectric interactions with other gas molecules, producing additional free electrons. Each of these in turn is also accelerated by the high voltage, generating more Townsend avalanches. The end result is a very large number of ionizations in the chamber called a *Geiger discharge* (Fig. 1-3), producing a billion or more ion pairs (3).

Meanwhile, the positive ions are being pulled toward the cathode, but because they are much larger than electrons, they move relatively slowly. There comes a point at which the anode is completely surrounded by an envelope or "hose" of positively charged gas molecules. Due to the high concentration of positive ions and the effective decrease in the anode's electric field, the electric field felt by free electrons no longer is high enough to cause gas multiplication. New electrons produced at this point (whether between the anode and hose or outside of the hose) will be more likely to recombine with a gas molecule than to cause another ionization. Thus the avalanche finally ends, after producing a large pulse of electricity. A pulse takes about 1 (μsec) to be created and about 50 to 100 μsec to dissipate.

The size of the electrical pulse created by each photon interaction does not vary significantly with either the applied voltage or the energy of the radiation. We will consider each electrical pulse registered by the Geiger counter to be the result of a single gamma ray causing a single ionization in the chamber as it passes through. Geiger counters are thus very sensitive, because a single interaction potentially produces a measurable event. They are very good for detecting small amounts of contamination.

Geiger counters operate in pulse mode. The units of measurement are either contamination units of counts per minute (cpm), or exposure units of mR/hr, or both. In cpm operation, each count represents one Geiger discharge. Calibration for exposure units uses a source with fixed gamma ray energy, so that the Geiger counter reading will change directly with the source strength, at that energy. However, the Geiger counter has significant energy dependence, such that when the source includes gamma rays with a variety of energies, the conversion to mR/hr is not correct for all of the gamma rays. Thus, the exposure reading varies with gamma ray energy, leading to a potential error factor of 2 to 3 (3). In addition, Geiger counters have a low efficiency for gamma rays of only a few percent (3). (Efficiency can be briefly defined as the number of gamma rays detected divided by the number arriving at the detector; see Appendix A for more information.) Its readouts should not, therefore, be used directly to calculate the radiation-absorbed dose. Rather, the Geiger counter is best used as a qualitative or semiquantitative indicator of the presence of radiation. It excels at this task because of its ability to detect small numbers of gamma rays.

Design Features

Geiger–Müller survey meters may operate via direct current from a battery or via alternating current from a wall outlet that is converted internally to direct current. The gas in the chamber is usually helium or argon, and it is often at less than atmospheric pressure, which minimizes the charge differential between anode and cathode that is required to bring about a Geiger discharge. Geiger counters are generally portable and ruggedly built. Some have audible alarms or "chirps" to allow the user to "hear" the radiation level. Like the ionization survey meter, the Geiger counter usually has a range knob or a logarithmic scale, giving it measurement abilities over several orders of magnitude. A low-level electronic discriminator is often included to prevent the detector from registering electrical noise and small-amplitude pulses as radiation events.

The pulse produced by a Geiger counter is quite large (about 10 V), which permits the detector module to be separated from the other electrical components by an insulated wire. The detectors come in a variety of configurations (**Figure 1-7**). A pancake detector (Fig. 1-7a) is designed to detect contamination by virtue of its unidirectional geometry and metal backing that scatters gamma rays back into the active volume. Another common geometry is a cylindrical detector called a G–M tube (Fig. 1-7b), which is used for general radiation detection purposes.

Like ionization survey meters, many Geiger counters have a thin entrance window to allow for measurement of particulate radiation, protected by either a wire screen or a removable cover. With the latter type, the cover must be removed if nonpenetrating radiation is to be counted in addition to penetrating gamma radiation. These end windows are quite fragile and easily broken. A perforated or damaged end window also allows the fill gas to escape, including the quench gas (see the following discussion). In addition, the pressure in the tube increases to the ambient pressure, rendering the unit nonfunctional.

Most Geiger counters read out in a rate meter format, in which the reading is expressed as cpm or mR/hr. The readout reflects the average number of pulses being received at the rate meter each second. As the amount of radiation increases, so will the rate meter output, but how fast it changes depends on the *time constant* τ of the rate meter. This is shown by illustration in **Figure 1-8**. A short time constant causes the Geiger counter reading to change quickly as the radiation field strength changes, but also allows it to bounce around a lot. A long time constant causes the reading to be steadier, but also to change more slowly than the instantaneous radiation field strength. Many instruments allow the operator to vary the time constant. In day-to-day operations, it is important to recognize that a quick response cannot be achieved with a long time constant, while a precise measurement cannot be made with a short time constant.

(a) Geiger counter with pancake detector

(b) Geiger counter with G–M tube detector

Figure 1-7 Geiger counters. (a) A pancake-type detector, useful for finding contamination. Photo courtesy of Capintec, Inc. (b) A typical Geiger–Müller tube attachment. Photo courtesy of Biodex Medical Systems, Inc.

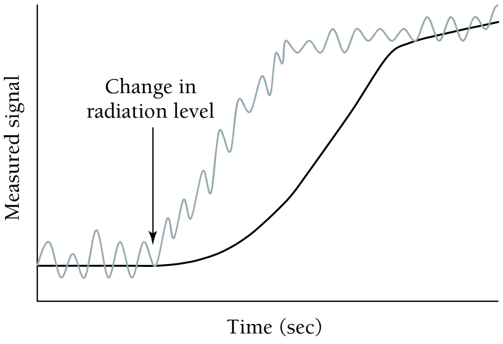


Figure 1-8 Illustration of short vs long time constants. The solid line illustrates a long time constant, while the gray line represents a short time constant.

One problem particular to Geiger counters is the possibility of a continuous avalanche. As electrons recombine with positive ions at the cathode in the final phase of the avalanche, it is possible for one to enter the orbital structure of the positive ion at an excited level and produce a UV photon as it drops down to ground level. If this occurs late in the tube's recovery process, the UV photon could cause a new ionization within the cathode and thus restart the avalanche, leading to either a continuous avalanche or a spurious event. A *quench gas* is added to the chamber at the time of manufacture to prevent this from happening. A quench gas is either an organic or (more likely) a halogen gas that will absorb UV photons without becoming ionized. Because this is taken care of in the manufacturing process, it is not a problem on a day-to-day basis.

Geiger counters are highly reliable instruments, but they tend to suffer from a lack of proper care. A Geiger counter that does not respond to a radioactive source has one of three problems: the battery is dead, the cable wires are broken, or the thin end window is damaged. Broken cable wires can result from dangling the detector while holding the cable. If the response of the Geiger counter to a radiation source is higher than expected, it may be contaminated. Because a Geiger counter may be hard to clean, this may render it unusable until the contamination has decayed to background.

Quality Control

The subject of *quality control* (QC) is a very important one in nuclear medicine. It can be defined as "an established set of ongoing measurements and analyses designed to ensure that the performance of a procedure or instrument is within a predefined acceptable range" (4). If a department does not pay close attention to QC, it cannot be certain that its clinical studies are producing correct results. Hence QC is emphasized in all parts of this text. Even though gas-filled detectors are quite simplistic in their operation, they too must be evaluated on a regular basis (**Table 1-2**).

Ionization Survey Meter and Geiger Counter

The important routine test on these instruments is their functionality for detection of radiation. A daily operations check includes a verification that the battery is working, a reading of background radiation level, and a check on the constancy of the detector's response to a radioactive source. Many ionization detectors have a "battery check" setting and a readout or rate meter output area that indicates whether the battery is supplying voltage in an acceptable range. If such readout is not available, the battery's functionality can be implied by the response to the constancy check. Determination that the background radiation level is in its normal range verifies that the detector has not become contaminated with radioactivity.

The *constancy check* measures a radioactive reference source in a reproducible geometry. The reading should be about the same (constant) from day to day, to within about 10% of an average value. When one of these detectors fails its constancy check, only a few possibilities exist for the source of the problem (**Table 1-3**) and these can easily be checked out.

Ionization survey meters and Geiger counters need to be checked for the accuracy of their output on an annual basis. *Accuracy testing* compares the reading given by the detector to the reading expected from a source with a known amount of radioactivity. In this case, the gamma constant of the reference standard provides the correlation between the activity and exposure rate reading. The *gamma constant* for a given radionuclide gives the radiation field strength (in mR/hr) produced by 1 mCi of that radionuclide at a specified distance (either 1 cm or 1 m). The expected radiation flux in mR/hr can be calculated by multiplying its gamma constant by the reference source's

Table 1-2

Recommended Quality Control Tests for Gas-Filled Detectors

Instrument	Test	Recommended Frequency
Dose calibrator	Constancy	Daily[1,2,3,4]
	Activity linearity	Quarterly[1,2,3,4]
	Accuracy	Annually[1,2,3,4]
	Geometry	At installation and after repair only
Ionization survey meter	Battery functionality	Daily[4]
Geiger–Müller survey meter	Constancy	Daily[4]
	Accuracy/calibration	Annually[4]

Note: All of these tests should be performed after an instrument has been serviced.

[1] Graham LS, ed. *Nuclear Medicine: Self-Study Program II: Instrumentation*. Reston, VA: Society of Nuclear Medicine; 1996:3,5.

[2] Christian PE. Radiation detection. In: Fahey FH, Harkness BA, eds. *Basic Science of Nuclear Medicine* [CD-ROM]. Reston, VA: Society of Nuclear Medicine; 2001.

[3] Klingensmith WC, Eshima D, Goddard J. *Nuclear Medicine Procedure Manual 2003–05*. Englewood, CO: Wick; 2003:20-1–20-4.

[4] Zanzonico P. Routine quality control of clinical nuclear medicine instrumentation: a brief review. *J Nucl Med*. 2008;49:1114–1131.

activity and dividing by the square of the distance between the source and the detector. There must be nothing but air between the source and the detector, and the distance should be great enough that the reference source looks like a point source.

Accuracy determination is usually performed annually by a commercial calibration laboratory, health physics consulting firm, or nuclear medicine product vendor. Each of the instrument's scale or range settings must be checked to verify accuracy. A Geiger counter or ionization survey meter is considered out of compliance if its accuracy reading is not within ±10% of the expected value. A *calibration process* is then employed, which involves adjusting the detector's output to bring it back into compliance. A detector that demonstrates 10 to 20% error can be used if a correction chart is supplied (5). Appropriate documentation and a sticker indicating the date of accuracy testing and/or calibration are supplied by the testing company.

Dose Calibrator

Dose calibrators are very reliable instruments that rarely have problems. They can remain stable to within ±0.1% over several years (3). However, because they are critical to the work of a nuclear medicine department, their operation must be checked daily. In addition, several quality control measures need to be done on a quarterly or annual basis, and all should be repeated after any repair. Table 1-2 lists the tests required for the dose calibrator.

A dose calibrator must be checked annually for accuracy using a reference standard whose activity is traceable to NIST. The procedure for accuracy testing (6) requires three separate measurements of the reference standard, which are averaged and compared to the known activity of the standard. This is repeated with two or three different radionuclides with different gamma ray energies. A dose calibrator is considered accurate if its reading is within ±5% of the reference standard activity (6).

The essential daily quality control test of a dose calibrator is a constancy reading of the activity of a long-lived source (usually Cs-137, although some users employ two or three radionuclides of varying energies). This test can be considered an accuracy evaluation only if the source is NIST-traceable. The constancy test verifies the proper operation of a dose calibrator on a given day, and it must therefore be performed every day that the dose calibrator is used, before its first clinical measurement. An error of ±10% (measured activity vs calibration data) or less is considered acceptable (6). It is also common practice to check the reading of the constancy source with each of the isotope selector buttons. In older electromechanical (as opposed to digital) dose calibrators, this step verifies that the electrical and mechanical components are providing correct outputs. For newer microprocessor-driven models, the numbers will not change unless the microprocessor is reprogrammed. At the time of the constancy check, the dose calibrator should also be checked for contamination and zeroed, and the voltage of the power supply noted.

One of the drawbacks of a constancy measurement is that it evaluates the operation of a dose calibrator at only one activity level. To know whether the dose calibrator is appropriately measuring at a variety of activity levels, a quality control test called activity linearity must be performed. *Linearity* refers to the ability of an instrument to measure variable quantities in a linear fashion. *Activity linearity* is defined as the ability of a dose calibrator to measure, in a proportional manner, sources with activities spanning several orders of magnitude. This test can be done in one of two ways. One is to measure a short-lived source such as Tc-99m at several time points over 2 to 3 days, plotting the measured activity vs time on semilogarithmic graph paper. The points should plot out linearly and match a Tc-99m decay plot. Consistent and accurate timing is necessary for this test; an error of 10 minutes (min) can give an apparent 2% linearity error (6).

Table 1-3

Troubleshooting Gas-Filled Detectors

Instrument	Problem	Possible Causes
Dose calibrator	Higher than expected constancy reading	• Contamination of dipper and/or liner
	Negative background reading or lower than expected constancy reading	• System zeroing engaged with contamination present; contamination has now decayed
Ionization survey meter, Geiger counter	Higher than expected constancy reading	• Contamination • Incorrect measuring distance or reference standard
	Lower than expected constancy reading	• Incorrect measuring distance or reference standard • Shielding material between standard and detector
	No reading on constancy check	• Dead battery • Broken cable (Geiger counter) • Thin end window integrity broken
Geiger counter	Reading decreases as distance decreases	• Dead time is affecting reading

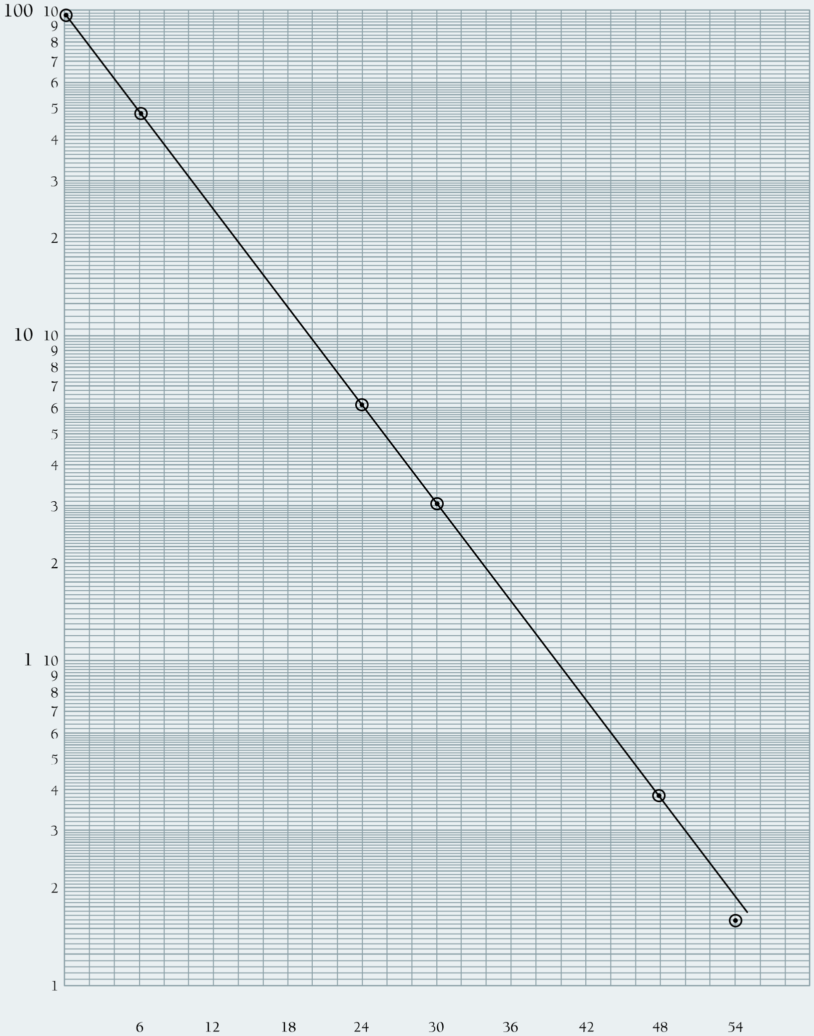
Sample Calculation 1-2 Activity Linearity Based on Decay

A dose calibrator is tested for activity linearity over 3 days, using a Tc-99m source, with the following results:

Day	Time	Activity
1	0800	96.4 mCi
1	1400	48.6 mCi
2	0800	6.08 mCi
2	1400	3.02 mCi
3	0800	0.381 mCi
3	1400	0.160 mCi

Plot these results on semilogarithmic graph paper to determine the linearity response of the detector. Decay-correct all other results to 0800 on day 2 to determine the variability relative to that value.

The graph looks very linear except for the last data point.



The decay-correction calculation assumes that decay is happening according to the half-life of Tc-99m, and it allows us to evaluate whether the dose calibrator is reflecting that accurately, at the high and low ends of the activity relative to the middle (where the dose calibrator is most likely to give a good measurement).

Continues

Simply apply the decay equation to each value:

$$\text{Activity (day 1, 0800): } 96.4\text{ mCi}\left(e^{-\left(\frac{0.693}{6.02\text{ hr}}\right)(24\text{ hr})}\right)$$
$$= 6.08\text{ mCi}.$$
$$\text{Activity (day 1, 1400): } 48.6\text{ mCi}\left(e^{-\left(\frac{0.693}{6.02\text{ hr}}\right)(18\text{ hr})}\right)$$
$$= 6.12\text{ mCi}.$$
$$\text{Activity (day 2, 1400): } 3.02\text{ mCi}\left(e^{-\left(\frac{0.693}{6.02\text{ hr}}\right)(-6\text{ hr})}\right)$$
$$= 6.02\text{ mCi}.$$
$$\text{Activity (day 3, 0800): } 0.381\text{ mCi}\left(e^{-\left(\frac{0.693}{6.02\text{ hr}}\right)(-24\text{ hr})}\right)$$
$$= 6.04\text{ mCi}.$$
$$\text{Activity (day 3, 1400): } 0.160\text{ mCi}\left(e^{-\left(\frac{0.693}{6.02\text{ hr}}\right)(-30\text{ hr})}\right)$$
$$= 5.05\text{ mCi}.$$

Note that the time becomes negative in the last three calculations in order to decay-correct backward in time. This dose calibrator demonstrates good activity linearity, with a range of values of 0.10 mCi or 1.6% around the nominal value of 6.08 mCi, down to the last value, which is only 83% of what the decay equation predicts.

An alternative method for evaluating activity linearity is to use a set of commercially available lead sleeves and a single high-activity source. The source is put into each of the sleeves, and the measured activity is compared to that expected based on the known amount of attenuation by the sleeve. After each reading is corrected by the known attenuation factor for each sleeve, the corrected values are averaged, and the percent error of each measurement relative to the average is obtained. The "sleeve method" for testing activity linearity is accomplished in a much shorter time frame than the decay method described above.

Activity linearity should be checked quarterly over a range of activities from the maximum activity dispensed down to 30 μCi (1.1 MBq). Percent error is calculated as (observed ÷ predicted × 100%). When the decay method is used, calculate the predicted amount of Tc-99m at each measurement time based on a reading between 1 and 50 mCi, because the dose calibrator is least likely to have measurement errors in this range. When the sleeve method is used, a long-lived source of known activity is used, and a table of predicted values is easily generated. **Figure 1-9** shows two examples of dose calibrators exhibiting nonlinearity, for different reasons. If the dose calibrator proves to have nonlinearity greater than ±10% in any activity range, it should be serviced (6).

Sample Calculation 1-3 Activity Linearity Using the Sleeve Method

The following readings are obtained on a Cs-137 source measured in a dose calibrator, using a set of lead attenuating sleeves. The four sleeves are combined to create a total of seven attenuation levels; the attenuation factors and the respective readings are given.

Attenuation Factor of Sleeve	Source Reading
1.000	214.0 mCi
3.379	62.9 mCi
5.088	42.1 mCi
17.694	12.15 mCi
41.368	5.22 mCi
139.226	1.56 mCi
206.937	1.04 mCi
696.105	0.31 mCi

Does this dose calibrator exhibit good activity linearity?

Multiply each reading by its corresponding attenuation factor.

Corrected readings:

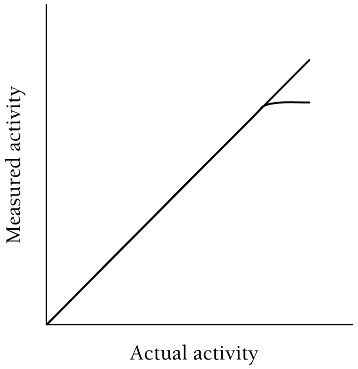
$$214.0\text{ mCi} \times 1.000 = 214.0\text{ mCi}.$$
$$62.9\text{ mCi} \times 3.379 = 212.5\text{ mCi}.$$
$$42.1\text{ mCi} \times 5.088 = 214.2\text{ mCi}.$$
$$12.15\text{ mCi} \times 17.694 = 215.0\text{ mCi}.$$
$$5.22\text{ mCi} \times 41.368 = 215.9\text{ mCi}.$$
$$1.56\text{ mCi} \times 139.226 = 217.2\text{ mCi}.$$
$$1.04\text{ mCi} \times 206.937 = 215.2\text{ mCi}.$$
$$0.31\text{ mCi} \times 696.105 = 215.8\text{ mCi}.$$

Choose 12.15 mCi as a reading unlikely to be affected by any problems, and use its corrected value as the 100% value for this test. Express all other corrected readings as a percentage of this value:

$$214.0\text{ mCi} = 99.5\%\text{ of }215.0\text{ mCi}.$$
$$212.5\text{ mCi} = 98.8\%\text{ of }215.0\text{ mCi}.$$
$$214.2\text{ mCi} = 99.6\%\text{ of }215.0\text{ mCi}.$$
$$215.9\text{ mCi} = 100.4\%\text{ of }215.0\text{ mCi}.$$
$$217.2\text{ mCi} = 101.0\%\text{ of }215.0\text{ mCi}.$$
$$215.2\text{ mCi} = 100.1\%\text{ of }215.0\text{ mCi}.$$
$$215.8\text{ mCi} = 100.4\%\text{ of }215.0\text{ mCi}.$$

The dose calibrator exhibits good activity linearity, because the largest deviation is 1.1% from the 100% value. If the percent values were greater than 10%, the dose calibrator would require servicing.

(a) Activity nonlinearity due to saturation of capacitor



(b) Activity nonlinearity due to recombination

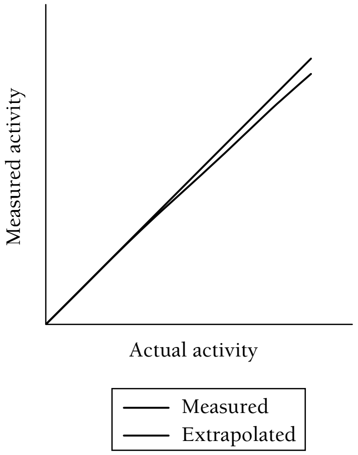


Figure 1-9 Graphs demonstrating poor activity linearity. (a) Activity nonlinearity due to saturation of capacitor. The measured activity line is flat at high activities, indicating that the chamber has exceeded the dose calibrator's ability to neutralize the large number of ion pairs being created. (b) Activity nonlinearity due to recombination. This graph, in contrast, shows a dose calibrator in which recombination is occurring at high activity levels, as indicated by a gradual separation between the measured and extrapolated lines as activity increases.

Finally, a dose calibrator may respond differently to different source containers, especially with certain kinds of radionuclides. When radionuclides that emit beta particles or low-energy gamma rays are measured, the dose calibrator's response is subject to inaccuracies, specifically when the radionuclide is contained in a glass vial vs a plastic syringe. These differences are evaluated by the manufacturer prior to installation of the dose calibrator and are collectively termed *geometry factors*. *Geometry testing* involves the measurement of a variety of radioactive sources in different geometric and volumetric configurations. A common procedure involves incremental additions of water to a radioactive solution, with a dose calibrator measurement after each addition (6). The procedure is performed with 3-ml syringes and 30-ml glass vials, both of which are commonly encountered in nuclear medicine practice. Care must be taken not to lose any radioactivity in the process, or the results will be invalidated. Again, the limit for geometry variation is ±10%; if this value is exceeded, mathematical corrections should be made to compensate.

While it is the manufacturer's responsibility to evaluate geometry issues, it is the user's responsibility to take geometric considerations into account when measuring a specific radionuclide. The particular radionuclides subject to geometric inaccuracies are generally listed in a chart that accompanies the dose calibrator. Geometry measurements need only be performed at installation and repair, so they should be kept on file for the life of the dose calibrator (6).

Limitations of Gas-Filled Detectors

Gas-filled detectors have several characteristics that make them quite useful in the detection of radiation. It is relatively easy to measure electric signals over several orders of magnitude, allowing these detectors to operate over a wide range of radiation intensity. They generally demonstrate excellent linearity of response (i.e., the measured value reported by the detector changes in direct relation to the strength of the radiation field). In addition, the unsophisticated design and simple electronics of these detectors combine to make them highly reliable instruments. But they have important drawbacks when compared to other categories of radiation detectors.

Efficiency for High-Energy Photons

Because the active volume of a gas-filled detector is a gas, these detectors have low efficiency for interaction with high-energy photons. In fact, most of the ionization events registered in a gas-filled detector result not from photon interactions in the gas itself, but rather from interactions in the detector walls, from which energetic secondary electrons escape into the gas chamber (3). The user of any gas-filled detector should be aware that many energetic photons do not interact in either the gas volume or the detector wall and are therefore not being detected. In addition, the relatively few ionizations produced in a gas-filled detector per radiation interaction (as compared to other types of detectors) prevent determination of the energy of that interaction.

Detection of Particulate Radiation

The measurement of charged particles with gas-filled chambers is problematic. Charged particles (alpha particles, beta particles, and electrons) interact via the electrical or Coulomb force. Because the Coulomb force operates over a distance, charged particles are constantly interacting, even in the low density of a gas-filled chamber. This fact makes an accurate measurement of their intensity in any of the gas-filled detectors discussed in this chapter imprecise, for two reasons. First, the walls of the chamber enclosing the gas volume may absorb the charged particles partially or completely, in which case the measurement may represent secondary electrons and/or secondary photons.

Second, if charged particles do get into the chamber (as they do in detectors that have a thin entrance window or open window), the measured ionization rate can have more than one meaning. Imagine two radioactive sources, each emitting only beta particles but with different beta particle energies, interacting in a radiation detector. The higher-energy beta particles, because they are traveling faster, interact with fewer molecules in the time they are inside the chamber. The slower, low-energy beta particles, on the other hand, have time to interact with more gas molecules as they travel through the chamber. In this situation, we cannot tell whether there are a few low-energy beta particles or a lot of high-energy beta particles—both situations can create similar numbers of ionizations in the gas. Gas-filled detectors can measure Bremsstrahlung radiation; this is commonly done with dose calibrators, albeit with necessary corrections (see previous discussion). But the operator should be aware of the potential for error when beta particles are the only radiation emissions.

Dead Time

This problem is encountered with Geiger counters and other detectors operating in pulse mode. *Dead time*, in the general sense, is the minimum time separation required in order that two radiation events be correctly recorded as two separate pulses. In a Geiger counter, this is determined by the time required for the positive ions surrounding the anode to dissipate. If a new radiation event occurs in the chamber before dissipation is complete, the electrical pulse produced will be smaller than usual and may not be detected by the pulse-counting electronics. The maximum observed count rate is limited to about 4,000 to 8,000 counts per second (cps) (corresponding to a true count rate of about 6,000 to 15,000 cps). Further, because the dead time is paralyzable, trying to count at rates above this maximum will lead to a decreasing count rate. A Geiger counter may register a very low count rate in the presence of a significant radiation field.

Summary

The small instruments discussed in this chapter are used daily in the nuclear medicine department. The operation of the department as a whole depends in a significant way on these simple but highly useful radiation detectors. Starting from the detection of the ionizations created by the interactions of gamma rays in air, they produce the measures of radiation field strength and activity needed by those who work with radiation. These instruments are rugged and reliable and will function properly for years if treated with a measure of care.

One must keep in mind, however, that while gas-filled detectors are relatively simple to operate, the user must be thoroughly knowledgeable of their strengths, weaknesses, and potential pitfalls. The use of an ionization survey meter to do contamination surveys or a Geiger counter with a pancake probe to monitor a radionuclide therapy patient would be likely to yield erroneous but apparently valid results. A dose calibrator reading may seem perfectly reasonable, even though the wrong isotope selector button has been chosen. An adequate understanding of the construction and operation of these instruments can prevent errors such as these.

References

1. Graham LS, ed. *Nuclear Medicine: Self-Study Program II: Instrumentation*. Reston, VA: Society of Nuclear Medicine; 1996:3,5.
2. Cherry SR, Sorenson JA, Phelps ME. *Physics in Nuclear Medicine*. 3rd ed. Philadelphia, PA: Saunders; 2003:91.
3. Knoll GF. *Radiation Detection and Measurement*. 3rd ed. New York, NY: John Wiley and Sons; 2000:146, 201, 212, 213, 215.
4. Christian PE. Radiation detection. In: Fahey FH, Harkness BA, eds. *Basic Science of Nuclear Medicine* [CD-ROM]. Reston, VA: Society of Nuclear Medicine; 2001.
5. Klingensmith WC, Eshima D, Goddard J. *Nuclear Medicine Procedure Manual 2003–05*. Englewood, CO: Wick; 2003:20-1–20-4.
6. Zanzonico P. Routine quality control of clinical nuclear medicine instrumentation: a brief review. *J Nucl Med*. 2008;49:1114–1131.

Additional Resources

Graham LS, ed. *Nuclear Medicine: Self-Study Program II: Instrumentation*. Reston, VA: Society of Nuclear Medicine; 1996:1–5.

Henkin RE, Boles MA, Dillehay GL, et al., eds. *Nuclear Medicine*. St. Louis, MO: Mosby-Year Book; 1996:Chapter 5.

Klingensmith WC, Eshima D, Goddard J. *Nuclear Medicine Procedure Manual 2003–05*, Englewood, CO: Wick; 2003:20-1–20-4.

Knoll GF. *Radiation Detection and Measurement*. 3rd ed. New York, NY: John Wiley and Sons; 2000:Chapters 5, 7.

Ramberg-Laskaris KL. Quality control in the radiopharmacy. *J Nucl Med Technol*. 1984;12:33–36.

Zanzonico P. Routine quality control of clinical nuclear medicine instrumentation: a brief review. *J Nucl Med*. 2008;49:1114–1131.