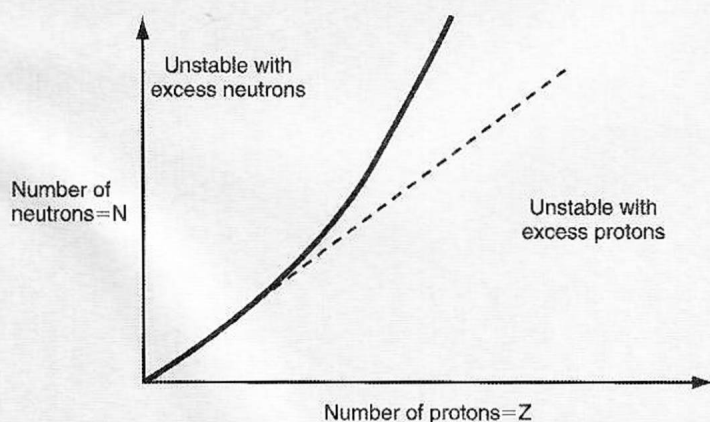


# Nuclear Medicine Physics

## A. Basic Concepts

1. **The line of stability** is a graph of the number of neutrons versus the number of protons in the nucleus of stable atoms. For elements with low atomic number ( $Z$ ), the line of stability is located where there are equal numbers of neutrons and protons. For elements with high  $Z$  numbers, the line of stability is located where there are more neutrons than protons. Above or below this line, the nuclei are unstable and decay with radioactive emissions.



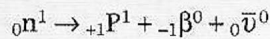
- Atoms with **excess neutrons** in the nuclei are created in a **nuclear reactor**, where there are huge fluxes of neutrons to bombard the stable atoms.
  - Atoms with **excess protons** in the nuclei are created in **particle accelerators**, such as linear accelerators and cyclotrons, which bombard stable nuclei with charged particles.
2. Atoms are designated by the following symbols.
    - $Z$  = atomic number = number of protons in nucleus
    - $N$  = neutron number = number of neutrons in nucleus
    - $A$  = mass number = sum of neutrons plus protons in nucleus =  $Z + N$
    - The symbol for the nucleus is  ${}_Z X^A$ ; for a carbon atom with six protons + six neutrons, the symbol would be  ${}_6 C^{12}$ .



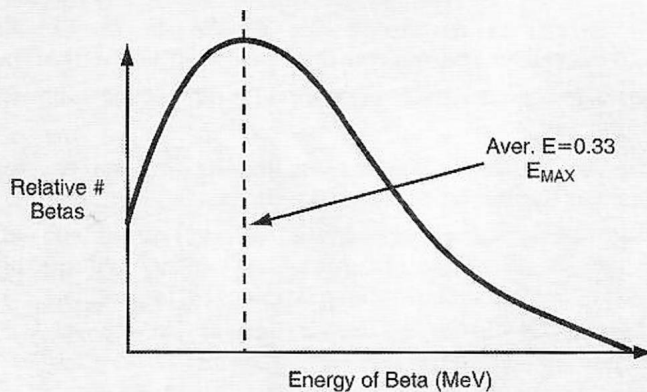
3. The definitions of different types of nuclei can be remembered by looking at the next-to-last letter in the applicable term, which indicates which particle remains the same.
- Isotope (*p*, proton) has *Z* same, *N* different, and *A* different (e.g.,  ${}_6\text{C}^{11}$ ,  ${}_6\text{C}^{12}$ ,  ${}_6\text{C}^{13}$ ).
  - Isotone (*n*, neutron) has *Z* different, *N* same, and *A* different (e.g.,  ${}_6\text{C}^{12}$ ,  ${}_7\text{N}^{13}$ ,  ${}_8\text{O}^{14}$ ).
  - Isobar (*a*, mass number) has *Z* different, *N* different, and *A* same (e.g.,  ${}_6\text{C}^{14}$ ,  ${}_7\text{N}^{14}$ ,  ${}_8\text{O}^{14}$ ).
  - Isomer (*e*, everything) has *Z* same, *N* same, and *A* same (e.g.,  ${}_{43}\text{Tc}^{99m}$ ,  ${}_{43}\text{Tc}^{99}$ —everything the same, only the energy in the nucleus different).
4. **Mass deficit** is the loss in mass that occurs when neutrons and protons are combined in the nucleus. The lost mass is converted into energy to hold the nucleus together.
- $E = mc^2$  = energy gained from loss of mass.  $E = 0.511$  MeV for an electron and  $E = 931$  to  $932$  MeV for a neutron or proton  $\cong 1$  amu (atomic mass unit).
  - Typically, nuclear binding energy is between 1 and 8 MeV per particle (nucleon), with an average of about 2 to 4 MeV per nucleon.
  - Sometimes the binding energy is negative, indicating the possibility of splitting the nucleus (fission).
5. Balancing nuclear equations means that the superscripts and subscripts all add up to the same value on both sides of the nuclear equation.
- For example,  ${}_5\text{B}^{11} \rightarrow {}_Z\text{X}^A + {}_2\alpha^4$
  - Superscripts:  $11 = A + 4$  or  $A = 7$
  - Subscripts:  $5 = Z + 2$  or  $Z = 3$
  - The decay product is:  ${}_3\text{X}^7 = {}_3\text{Li}^7$ .
6. All radioactive atoms eventually decay. The rate of decay is an exponential process.
- $[N/N_0] = \exp[-\lambda t]$ , where  $\exp$  is the natural number “*e*” = 2.7182....
  - $N_0$  = the initial number of radioactive atoms.
  - $\lambda$  = the decay constant for the particular radioactive nucleus =  $0.693/T_{1/2}$ .
  - $T_{1/2}$  = the half-life or time in which half the radioactive atoms decay.
  - $A = \text{activity} = \lambda \times N$  = fractional decays per unit time.
  - For each multiple of elapsed time (*t*) equal to  $T_{1/2}$ , the activity decreases by  $1/2$ .
  - Activity can be measured in new SI units of **becquerels (Bq) = 1 decay per second (dps)**.
  - An older unit of activity is **1.0 curie (Ci) =  $3.7 \times 10^{10}$  dps**.
  - **Example:** If the  $T_{1/2}$  of Tc-99m is exactly 6 hours and 120 mCi are delivered at 6:00 AM, how much activity will remain at midnight of the same day?
  - **Solution** to example is as follows:
- $t = 18$  hours;  $t/T_{1/2} = 18.0$  hours/6 hours = 3.0 half-lives
- $[N/N_0] = (1/2) \times (1/2) \times (1/2) = (1/8)$
- $A = (1/8) \times 120$  mCi = 15 mCi

7. **There are five basic nuclear decay processes** that occur for most radioactive isotopes in nuclear medicine: positron emission ( $\beta^+$ ), electron capture (EC), beta decay ( $\beta^-$ ), isomeric transitions (ITs), and alpha emission ( $\alpha$ ).

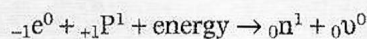
- **Beta minus ( $\beta^-$ ) decay occurs for radioactive atoms with excess neutrons.** In the nucleus, a neutron (n) decays into a proton (P) + electron ( $\beta^-$ ) + antineutrino ( $\bar{\nu}$ ).



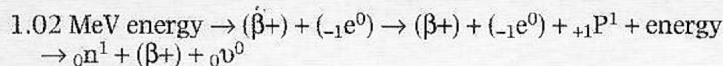
- A **beta particle** is an electron that originates in the nucleus. If the electron originates in orbital shells of an atom, it is simply an electron.
- The beta electron and the antineutrino are ejected from the nucleus, and the nucleus recoils. Thus, three objects are sharing the energy, and the average energy of the beta is about 33% of the maximum energy.
- The nucleus loses one neutron that decays to produce one proton, moving the new nucleus toward the line of stability.
- A neutrino ( $\nu$ ) is a particle with no charge and no rest mass that travels very fast and penetrates through most matter.
- Following ejection of the beta, there can be further loss of energy by gamma emission.



- **Electron capture (K-capture) occurs for radioactive atoms with excess protons.** A K-shell electron (e) orbiting the atom is captured by the nucleus. The electron combines with a proton in the nucleus to form a neutron.



- The neutrino is ejected from the nucleus.
  - The number of protons in the nucleus decreases by one and the number of neutrons increases by one, moving the new nucleus toward the line of stability.
  - After the decay, the K-shell is missing an electron, which results in electron transitions and the emission of characteristic x-rays.
- **Positron ( $\beta^+$ ) decay occurs for radioactive atoms with excess protons.** Positron decay begins when 1.02 MeV of nuclear energy is used to create a regular electron and an antiparticle, positive electron ( $\beta^+$ ). The created electron in the nucleus then combines with a proton to create a neutron. The neutrino and the positron are ejected from the nucleus.



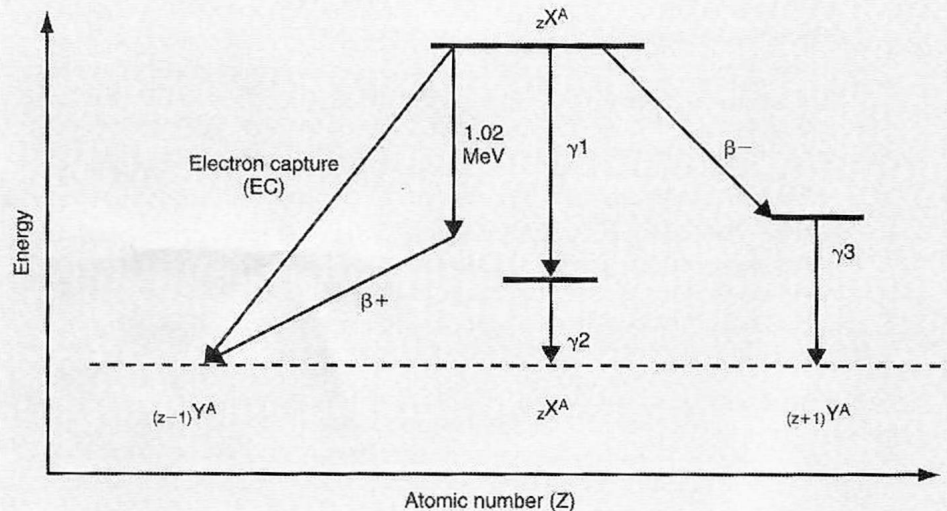
- The neutrino and the positron are ejected from the nucleus, and the nucleus recoils.

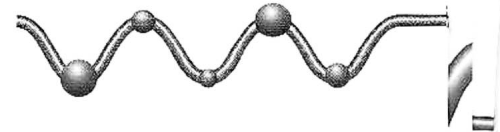
- (b) The number of protons in the nucleus decreases by one, and the number of neutrons increases by one, moving the new nucleus toward the line of stability.
- (c) After the decay, there can be further loss of energy by gamma ray emission.
- **Isomeric transitions** ( $\gamma$ , gamma ray emission) occur for radioactive atoms with excess energy in their nuclei.

Excess energy in nucleus  $\rightarrow \gamma$  or  $e + x\text{-ray}$  or  $e + \text{Auger } e$

- (a) A **gamma ray** is a photon that originates in the nucleus. If the photon originates outside the nucleus, it is called an x-ray.
- (b) **Internal conversion** is a process in which the gamma ray occasionally interacts with an inner shell orbital electron on the way out of the nucleus from which it was emitted. The orbital electron is ejected and is called an **internal conversion electron**. The remaining electrons then make a transition to fill the vacancy in an inner shell and produce a **characteristic x-ray**. Internal conversion electrons can be distinguished from beta particles because betas have a range of energies and conversion electrons are monoenergetic.
- (c) A third alternative is the emission of the **internal conversion electron**, but the characteristic x-ray interacts with an outer shell electron in the same atom, and an **Auger electron** is emitted and the x-ray disappears.
- (d) The alternatives are (1) just a gamma ray, (2) no gamma ray but instead an internal conversion electron + characteristic x-ray, and (3) no gamma ray but instead an internal conversion electron + an Auger electron.
- **Alpha particle emission** typically occurs for radioactive atoms with a high atomic number of  $Z > 80$ .
- (a) An **alpha particle** is a helium atom missing its orbital electrons. An alpha is two neutrons plus two protons.
- (b) Typically, these radioactive atoms (after decay) continue to emit alpha particles in a series of decays. Each emission reduces the mass number by 4 units and the atomic number ( $Z$ ) by 2 units.
- (c) The **four well-known series with a chain of alpha particle decays** are thorium ( $4N$ ), neptunium ( $4N + 1$ ), uranium ( $4N + 2$ ), and actinium ( $4N + 3$ ). The phrase " $4N + 1$ " means that the mass number of each product in the decay can be expressed as 4 times an integer plus one. **The radium-to-radon decay is part of one alpha series decay chain that is " $4N + 2$ ."**

8. Energy level diagrams are used to describe three different decay processes.





9. Some important radioisotopes that are used in nuclear medicine are listed in the table.

ISOTOPE	PRINCIPAL EMISSION	PERCENT EMISSION	ENERGY (keV)	HALF-LIFE
${}^3_1\text{H}$	$\beta^-$	100	18.6	12.5 yr
${}^{14}_6\text{C}$	$\beta^-$	100	156.1	5730 yr
${}^{32}_{15}\text{P}$	$\beta^-$	100	1708	14.3 days
${}^{57}_{27}\text{Co}$	$\gamma_2$	85.9	122	270 days
${}^{67}_{31}\text{Ga}$	Many $\gamma$ 's	46	184–394	78.1 hr
${}^{81m}_{36}\text{Kr}$	$\gamma$	100	191	13.0 sec
${}^{99}_{42}\text{Mo}$	Many $\beta$ particles	19 $\rightarrow$	740–778	66.7 hr
${}^{99m}_{43}\text{Tc}$	$\gamma_2$ and $\gamma_3$	88	140.5–142.6	6.05 hr
${}^{111}_{49}\text{In}$	$\gamma_1$ and $\gamma_2$	90 and 94	172 and 247	2.81 days
${}^{113m}_{49}\text{In}$	$\gamma_1$	62.1	392	99.4 min
${}^{123}_{53}\text{I}$	11 $\gamma$ 's	85 ( 2 $\gamma$ 's)	159 and 529	13.0 hr
${}^{125}_{53}\text{I}$	$\gamma$ and X photons	147	27–35	60.2 days
${}^{131}_{53}\text{I}$	14 $\gamma$ 's	87 $\rightarrow$	284–364	8.06 days
${}^{133}_{54}\text{Xe}$	Many $\gamma$ 's	36 $\rightarrow$	81	5.3 days
${}^{201}_{81}\text{Tl}$	X and $\gamma$ photons	94 $\rightarrow$	69–82	73.0 hr

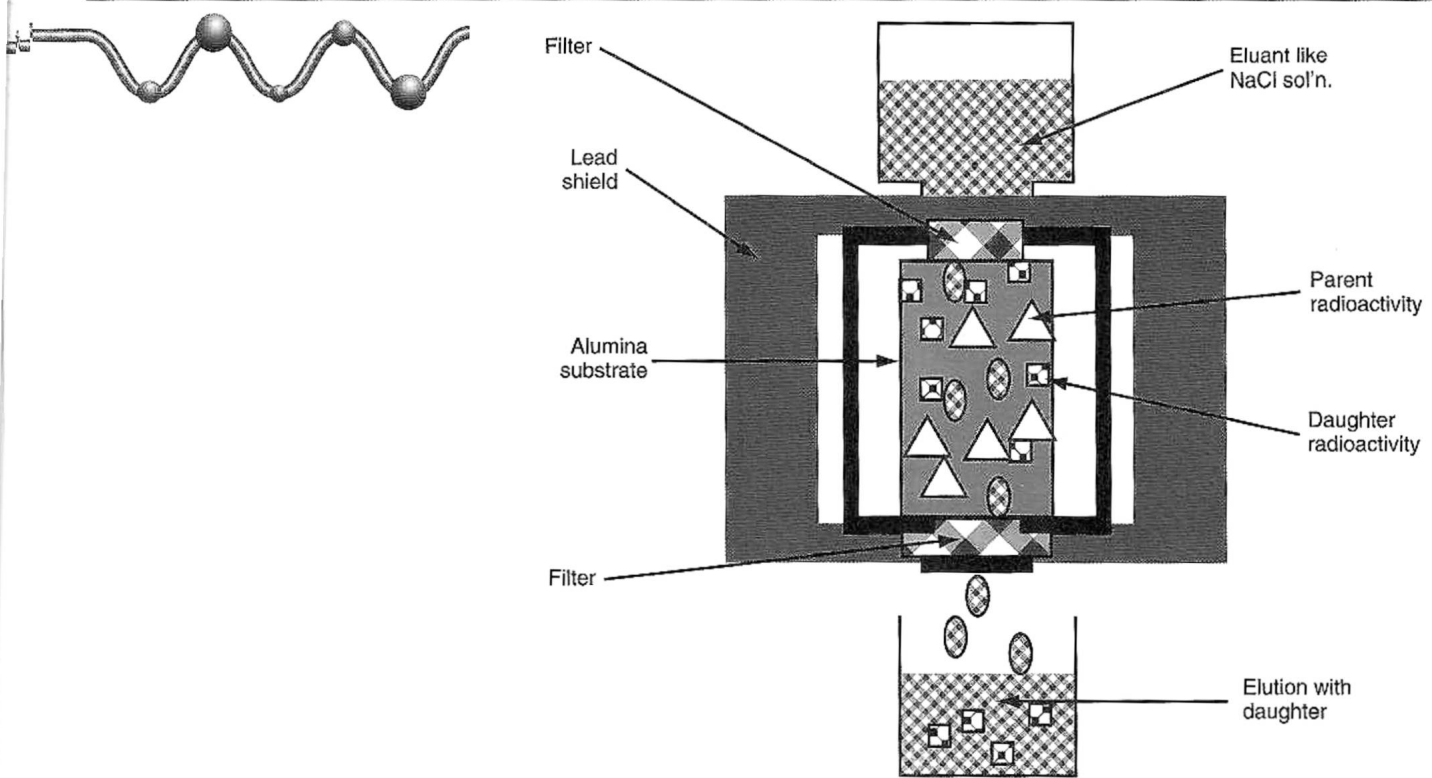
10. There are other radioactive interactions such as fission, fusion, and  $(n, \gamma)$  interactions. However, most of these processes are not normally included in routine nuclear medicine imaging.

## B. Radionuclide Generators

- A **generator** contains an alumina (or other substrate) **column** unto which is coated a **parent radioactive material**.
  - A **daughter** radioactive material is produced by the decay of the parent material.
  - An **eluant** is a solution that is passed through the generator to dissolve the daughter radioactive material from the column.
  - The parent material is chemically different and is not dissolved by the eluant.
  - A **microscopic filter** is used to stop debris, include flakes of the column with the parent, from passing through to a receptacle.
  - The **elution** contains only the daughter (unless there is **breakthrough**, which is contamination by the parent by flakes from the column). The daughter decays at a rate dictated by its half-life.
  - As more of the parent source decays, more daughter material is created.
  - There are two competing processes:** The **parent decays** at a rate dictated by its half-life, creating more daughter material, and the new **daughter decays** with a different rate dictated by the daughter's half-life.
  - Equilibrium is reached after a period of time in which the activities of the parent and daughter are nearly equal (see figure shown on next page).
- The **generator principle** states that at **equilibrium, the activities** of the parent and daughter are almost the same.

$$A_d \cong [\lambda_d / (\lambda_d - \lambda_p)] \times A_p \cong A_p$$

$$\text{where } \lambda = 0.693 / T_{1/2}.$$



- The **parent activity** is decaying at a rate controlled by its half-life.

$$A_p = (1/2)^y \quad \text{where } y = (t'/_p T_{1/2})$$

$y = (\text{time since calibration}/\text{half-life parent}).$

- **Buildup of activity** of the daughter after elution depends on the half-life of both the parent and the daughter.

$$A_d \cong A_p [1.0 - (0.5)^X] \quad \text{where } X = (t/_d T_{1/2})$$

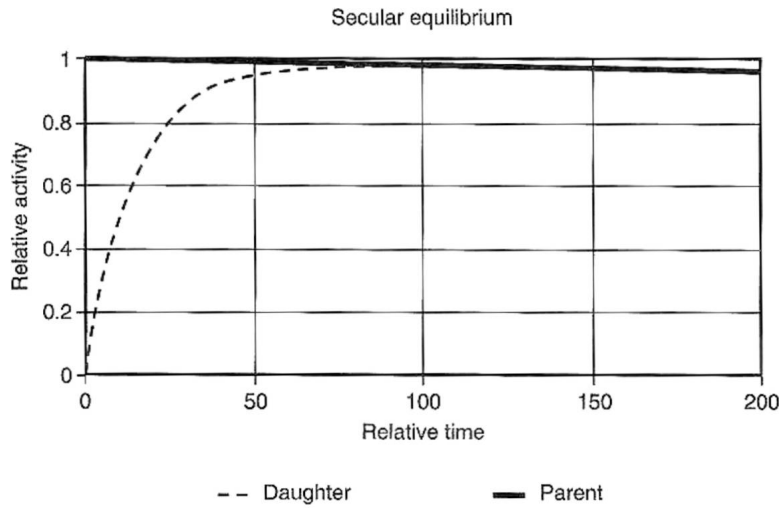
$X = (\text{time since elution}/\text{half-life daughter}).$

- An example is shown in the table for a Tc-99m generator. The half-life of the parent is about 67 hours, and the half-life of the daughter is about 6 hours.

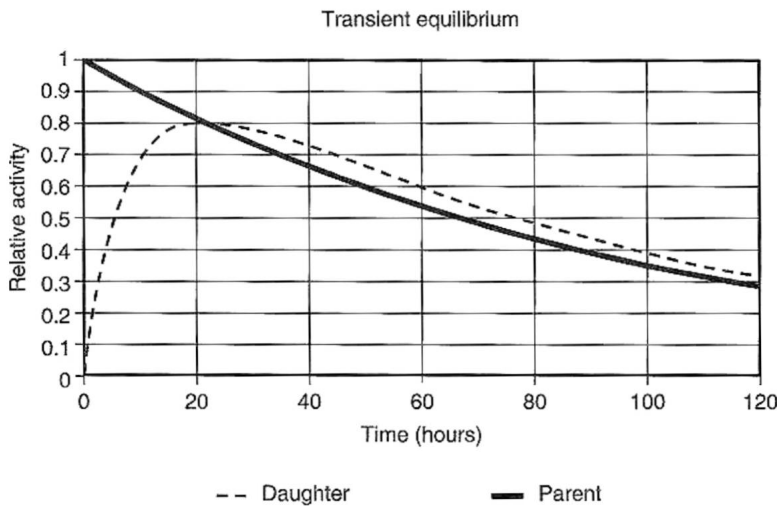
TIME SINCE ELUTION (HR)	$X = t/T_d$	$[1 - (0.5)^X]$	$Y = t/T_p$	$A_p$	$A_d$
0	0	0.0	0	$1.0 A_0$	0
6	1	0.5	0.090	$0.94 A_0$	$0.47 A_0$
12	2	0.75	0.179	$0.88 A_0$	$0.66 A_0$
18	3	0.875	0.269	$0.83 A_0$	$0.73 A_0$
24	4	0.938	0.358	$0.78 A_0$	$0.73 A_0$
36	6	0.984	0.537	$0.69 A_0$	$0.68 A_0$
48	8	0.996	0.716	$0.61 A_0$	$0.61 A_0$
67	11.2	0.9996	1.0	$0.50 A_0$	$0.50 A_0$

3. In **secular equilibrium**, the half-life of the parent is much, much longer than the daughter's half-life ( $T_p \gg T_d$ ). After elution, it takes about  $4T_d$  for the activity of the daughter to approach the activity of the parent. Both materials then

stay at equilibrium without much change in activity for a very long time. See the graph below.



4. In **transient equilibrium**, the half-life of the parent is appreciably longer than the daughter's half-life by a factor of 10 to 20 times ( $T_p > T_d$ ). After elution, it takes about  $4T_d$  for the activity of the daughter to exceed slightly the activity of the parent. Both materials then decay at equilibrium with the decay rate of the parent as long as they are mixed together.



5. For a **Tc-99m generator**, **federal regulations** limit the amount of Mo-99 impurity allowed in the eluant.
- No more than 1.5  $\mu\text{Ci}$  of  $\text{Mo}^{99}$  per 1.0 mCi of  $\text{Tc}^{99\text{m}}$  eluant
  - No more than 5.0  $\mu\text{Ci}$  of  $\text{Mo}^{99}$  per patient injection
  - The beta particles from  $\text{Mo}^{99}$  contribute significantly to the radiation dose to the patient.
  - **The Mo breakthrough test** is done by placing Tc-99m eluant in a leaded container. The lead container attenuates most of the 140-keV gammas

from technetium, but the high-energy (740- to 780-keV) gammas of Mo-99 penetrate the lead and are counted.

### C. Radiopharmaceutical Dosimetry

1. **For charged particles and nonpenetrating photons ( $E < 30 \text{ keV}$ ),** the energy is deposited locally. At the location at which the radiopharmaceutical biologic concentrates, the energy is released in emissions deposited at the same organ site.

$$D_{np} = 3.07 \times F_{organ} \times (A_0/M) \times T_{eff} \times E \text{ in units of cGy}$$

where  $F_{organ}$  = fraction of injected activity concentrating in the organ,  $A_0$  = injected activity in  $\mu\text{Ci}$ ,  $M$  = mass of the organ in grams,  $T_{eff}$  = effective half-life in hours, and  $E$  = average energy of the radiation in MeV.

- **Concentration:** Radiation dose increases with more activity concentration in the organ.
  - **Activity:** Radiation dose increases with more injected activity.
  - **Effective half-life:** Radiation dose increases with longer effective half-life.
  - **Energy:** Radiation dose increases with higher particle energy.
  - **Organ mass:** Radiation dose decreases with larger organ mass. If the same radioactivity intended for an adult is injected into a baby, the radiation doses are greater because of the smaller organ sizes.
2. **The effective half-life ( $T_{eff}$ )** is the effective time that the radioisotope stays inside the body. The elimination of radioisotope is by two different methods: excretion with a biologic half-life ( $T_B$ ) and photon emission decay with a physical half-life ( $T_P$ ).

$$T_{eff} = (T_B \times T_P) / (T_B + T_P)$$

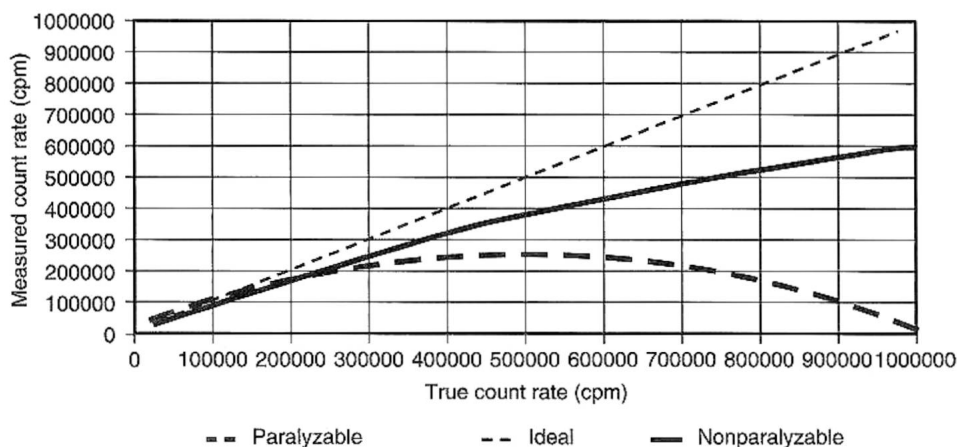
- **If  $T_B \cong T_P$ ,** the effective half-life is approximately  $0.5 \times T_P$ .
  - **If either the  $T_B \gg T_P$  or  $T_B \ll T_P$ ,** the effective half-life is slightly less than the smaller of the two half-lives.
  - If the two half-lives are just a little different, calculate half of each half-life, and the effective half-life is between those two values.
  - For example, if  $T_P = 6$  hours and  $T_B = 10$  hours, the  $T_{eff}$  is nearly midway between 0.5 times each half-life or midway between 3 hours and 5 hours.  $T_{eff} \cong 4$  hours. It is precisely equal to 3.75 hours; the approximation is reasonably accurate.
3. **For gamma ray radiation,** some of the radiation is deposited locally, and some escapes the body entirely without depositing any energy internally. The activity in some organs irradiates other nearby organs. The calculation for gamma-emitting radiopharmaceuticals is complex; computer Monte Carlo calculations in a simulated human are used to assess the dosimetry.

$$D_{gamma} = F_{organ} \times (A_0/M_{source}) \times (1.44T_{eff}) \times S \text{ (organ source} \rightarrow \text{organ target)}$$

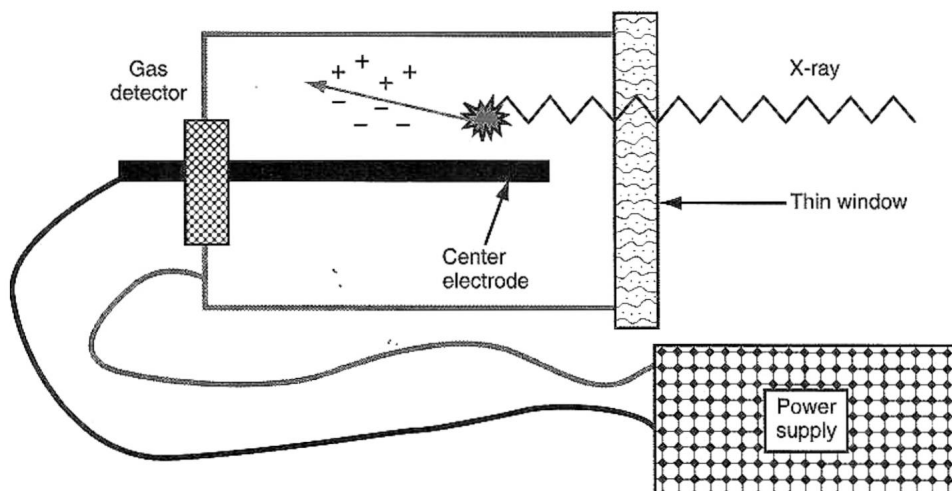
- Many of the effects are the same as for nonpenetrating radiation.
  - The  $S$  values are found in tables for different isotopes and different source and target organs.
4. In general, nuclear medicine studies aim to use enough radioactivity to obtain good photon statistics.
    - Critical organ radiation doses for most examinations are nearly 5 cGy.
    - Whole body radiation doses are 0.5% to 5% of the critical organ dose.

## D. Radiation Detectors

- Efficiencies of detector systems fall into different categories.
  - Geometric efficiency** is the fraction of all emitted radiation that hits the detector.
  - A  **$4\pi$  detector** has all the radiation impinging on its surface, such as an NaI crystal with a hole drilled into it (a well counter).
  - A  **$2\pi$  detector** has 50% of radiation passing into its surface.
  - Intrinsic efficiency** is the fraction of the incident radiation that the detectors actually measure.
  - Overall efficiency** = geometric efficiency  $\times$  intrinsic efficiency.
- Dead time** is the time after a detected event in which the detector cannot register another interaction.
  - With **paralyzable detectors**, additional events occurring during the dead time extend the duration of the dead time. Very high radioactivity can cause the detector system to register zero count rate.
  - With **nonparalyzable detectors**, additional events occurring during the dead time do not extend the dead time, but they are not measured. Very high radioactivity causes the system to reach some maximum count rate that does not increase with more radioactivity.

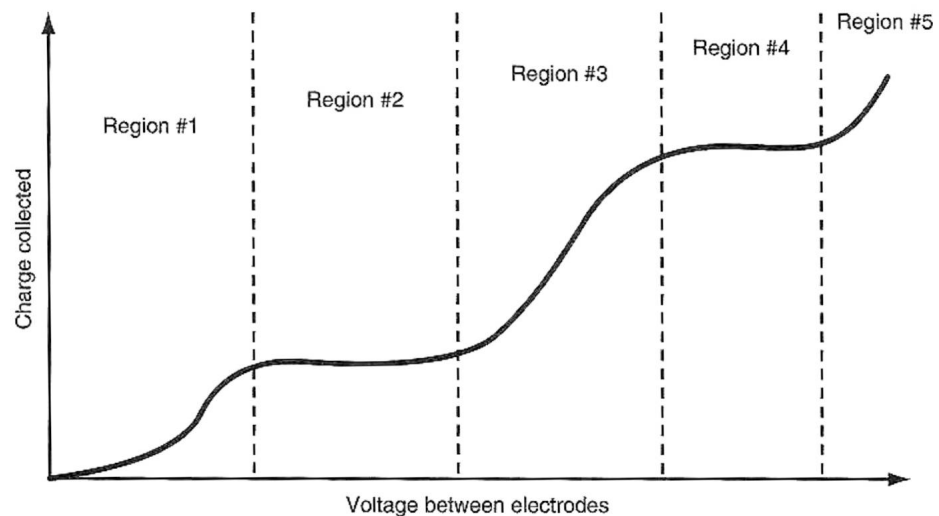


- Gas detectors have a voltage between a center electrode and an outer shell that collects the charge created by ionizing radiation.

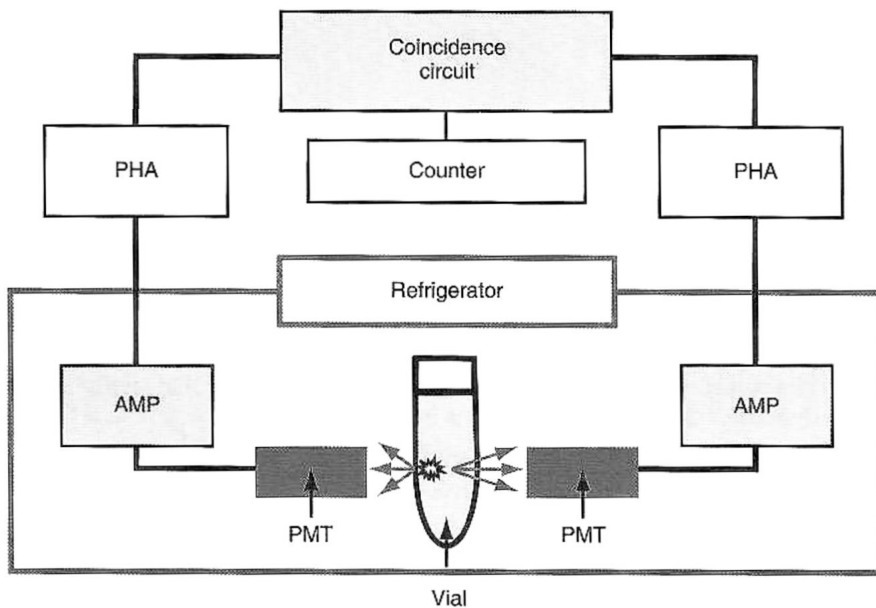
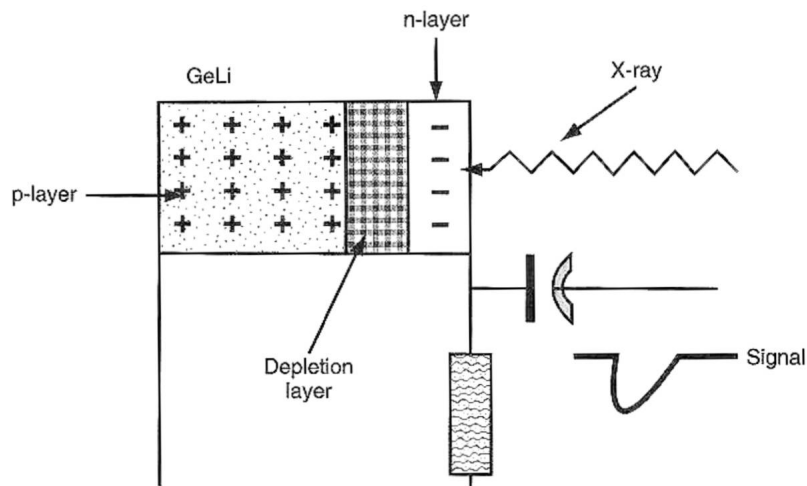




4. Gas detector systems fall into several different categories. There are five voltage regions of gas detectors.
- **Region 1: Recombination region** of the ionization curve; the detector is not useful. Typically at least 200 to 400 volts are needed to prevent recombination.
  - **Region 2: Ionization region**; used by the detector to collect all ion pairs created inside the gas detector. In this region, exposure (in mR or R) can be measured.
  - **Region 3: Proportional region**; creates additional charge by using higher voltages to create more ion pairs for each initial ionization. The charge is proportional to but greater than the initial ionization. Proportion detectors are used to assess charged particle radiation such as betas and alphas and neutrons.
  - **Region 4: Geiger-Mueller (GM) region**; uses a few ionizations in gas to amplify to a large amount of charge. The size of the charge is not related to the initial ionization. The GM region is useful only for detecting and counting a small amount of radioactivity. Radiation doses cannot be determined in this region.
  - **Region 5: Avalanche region**; the voltage at which spontaneous discharges can occur without any radioactivity present. The detector can be damaged in this region by continuous discharges initiated by the high voltage, causing a spark.



5. **GeLi solid-state detectors** are often used to measure the energy spectra of photons because of their ability to measure small differences in energy of 2 to 3 keV.
- Ionization is created directly in solid-state material and collected.
  - These detectors are usually cooled with liquid nitrogen to reduce background signals (see top figure on next page).
6. **Liquid scintillation detectors** are used to measure small amounts of low-energy charged particles in fluids, such as  $C^{14}$  in urine or blood, and wipes of radioactive materials that emit low-energy charged particles.
- **Refrigeration** of units is used to reduce photomultiplier tube (PMT) noise.
  - **Quenching** by water and other substances can reduce signal.
  - **Coincidence detection** uses two PMTs to look for a simultaneous signal to avoid counting noise pulses. In the figure, PHA stands for pulse height analyzer, AMP stands for amplifier circuit (see bottom figure on next page).

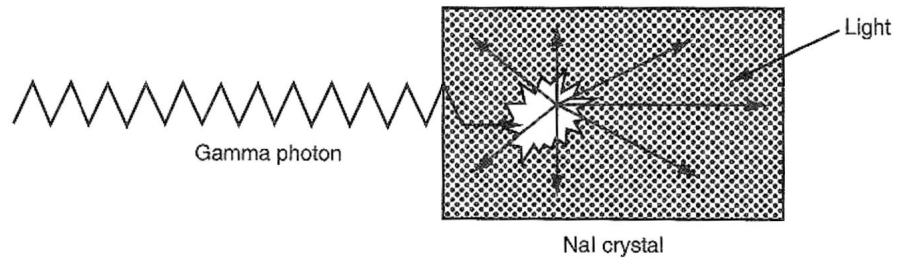


## E. NaI Crystal Scintillation Detectors

- Scintillation crystals such as sodium iodide (NaI) or cesium iodide (CsI) convert some of the energy deposited in the crystal by gamma and x-ray photons into light.
  - In photoelectric interactions, all the photon energy is deposited in the crystal.
  - For Compton interactions, only a portion of the energy is deposited in the crystal.
  - The most energy deposited with Compton scatter is for a 180-degree scatter in the crystal:
 
$$\Delta E = (2\alpha E_0) / [1 + 2\alpha]$$
 where  $\alpha = E_0 / 511 \text{ keV}$  and  $E_0 = \text{initial energy}$ .
  - The least amount of energy deposited is zero in a zero-degree Compton scatter.

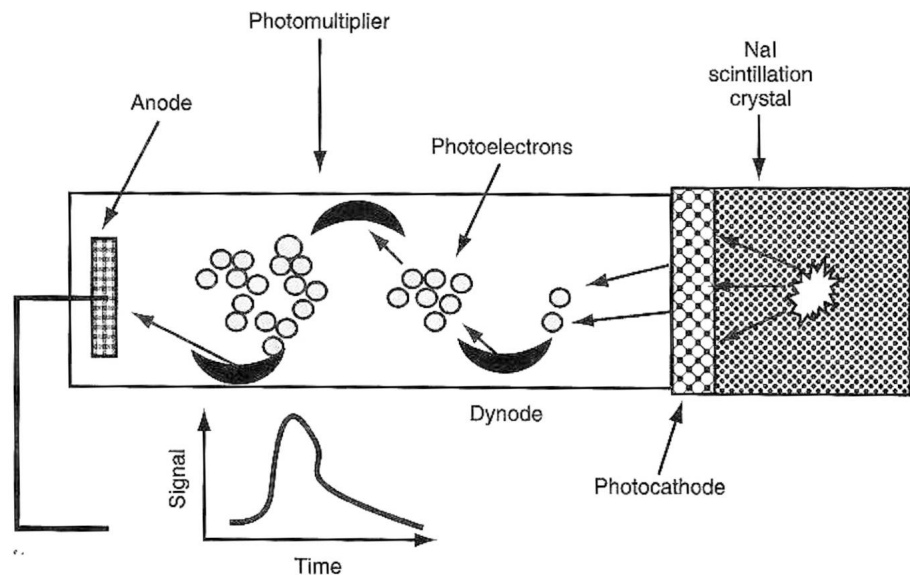


- The light emitted is directly proportional to the energy deposited in the crystal. The percentage varies from about 8% up to 25% to 50%.

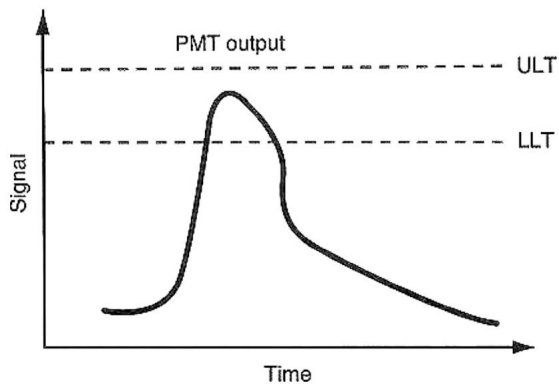


COMPTON SCATTER ANGLE (DEGREES)	ENERGY DEPOSITED IN CRYSTAL FOR Tc-99m 140-keV PHOTONS
0	0
45	10.4 keV
90	30.1 keV
135	44.6 keV
180	49.5 keV

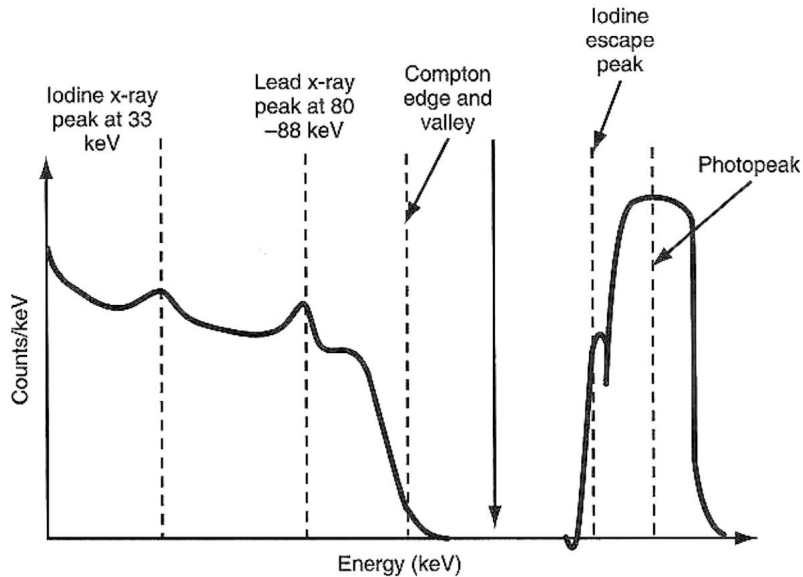
2. PMTs capture the light from the scintillation crystal and convert it into an electrical signal whose amplitude is proportional to the light emitted, which is in turn proportional to the energy deposited in the crystal.
  - The photocathode captures the light and converts it into a few electrons.
  - There are several hundred volts between dynodes.
  - The voltage accelerates the electrons, and, when they collide with the dynodes, the number of electrons is multiplied each time.
  - With many dynodes, the number of electrons is multiplied many times to produce a strong signal that is proportional to the amount of energy deposited in the crystal.



3. A **pulse height analyzer (PHA)** counts only signals with an amplitude greater than a lower level threshold (LLT) and less than an upper level threshold (ULT).



4. A **multichannel analyzer (MCA)** is a series of PHAs that are adjacent to one another so that the entire photon spectrum of all gamma photons interacting in the scintillation crystal with different amounts of energy deposited is recorded.



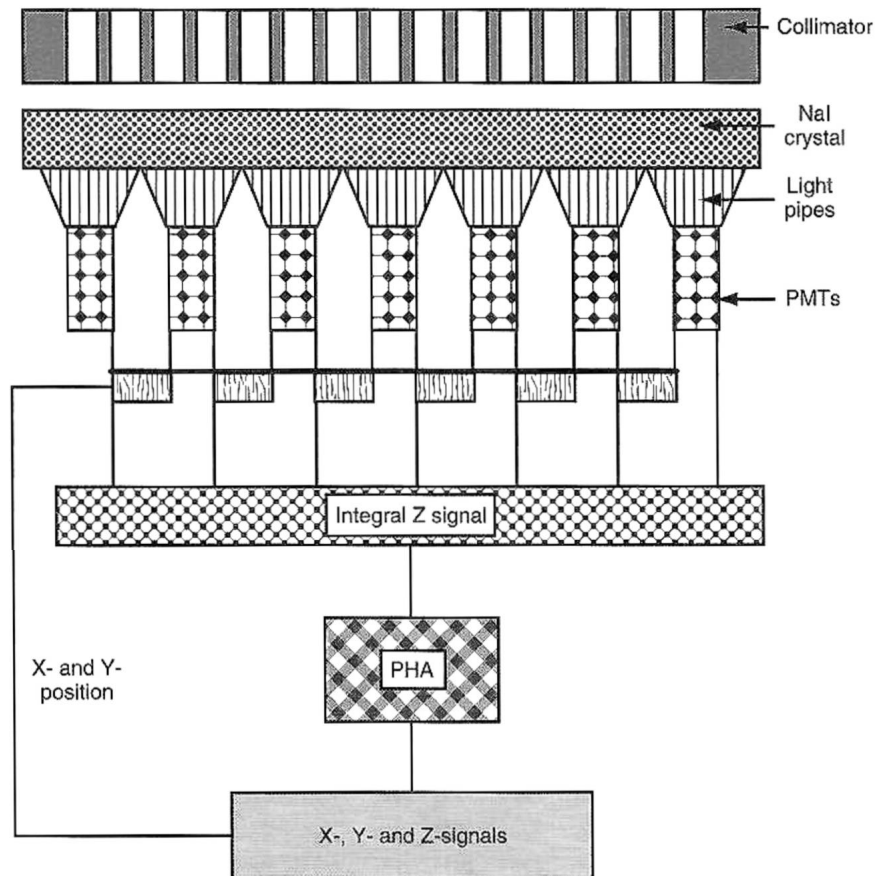
- At the lowest energy, the peak is due to **dark current** in the PMT.
- The **iodine x-ray peak** occurs at 33 keV. It is a peak related to a photoelectric interaction in the iodine atoms of the crystal followed by escape of ionization and the iodine characteristic x-ray depositing its energy into the scintillator crystal.
- The **lead x-ray peak** occurs at 80 to 88 keV. The peak is due to characteristic x-rays coming from the lead that surrounds the detector.
- The **Compton edge** is the most energy deposited from a single 180-degree Compton scatter in the scintillation crystal.
- The **Compton valley** is the difference between the most energy deposited in a single 180-degree scatter in the crystal and a photoelectric event with all the energy deposited in the crystal.
- **X-ray escape peak** refers to the photoelectric deposition of all the energy with the characteristic x-ray of iodine escaping from the crystal. The energy is at 33 keV below the photopeak energy.



- **FWHM** (full width at half maximum) is the width in energy of the photopeak at half its maximum counts. It is a measure of the energy resolution of the detector.
- A **coincidence peak** occurs when two photons interact simultaneously in the crystal, which causes them to look like a single photon with double the energy.

## F. Scintillation Cameras

- The scintillation camera uses a large-diameter (10- to 14-inch) NaI crystal that is either circular or rectangular to stop the photons and create light in proportion to the energy deposited in the crystal. The light is then detected by a large number of PMTs positioned around the crystal.
  - **Z (or integral) signal** is the sum of the signals from all of the PMTs. This signal is proportional to the **energy deposited** in the crystal by the gamma.
  - **X and Y (or differential)** is related to the **location** of the signal in the crystal.

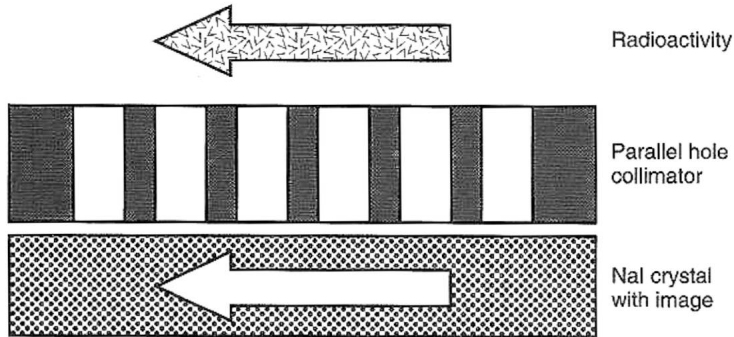


- Light pipes gather light in the crystal and direct it into PMTs.
- NaI crystal thickness ranges from 0.5 to 0.25 inch. Thinner crystals have better spatial resolution, but they are less efficient at detecting gamma photons. Thicker crystals are more efficient at detecting gammas but have degraded spatial resolution.
- The PHA counts only photons that deposit all their energy in the crystal; thereby, scattered photons that have lost energy externally are rejected.

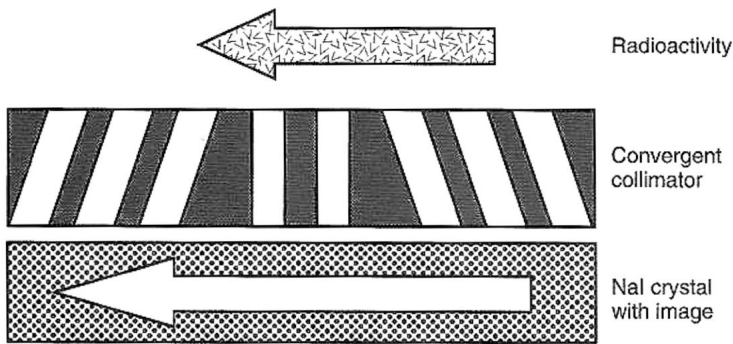


2. **Collimators** are used to cause gammas from a particular point in space to interact only with a corresponding point in the crystal. Collimators consist of holes in a thick lead plate that is mounted in front of the scintillation crystal. There are basically four types of scintillation camera collimators.

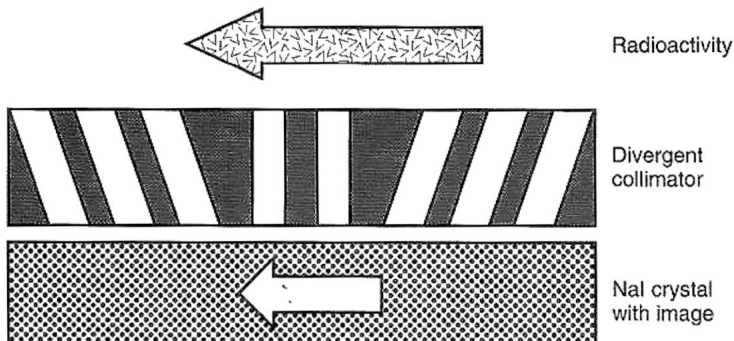
- **Parallel hole collimators** are the most common type. These collimators neither magnify nor minify the image.



- **Convergent collimators** enlarge the image by means of holes that cause the image to converge to a point in front of the collimator.



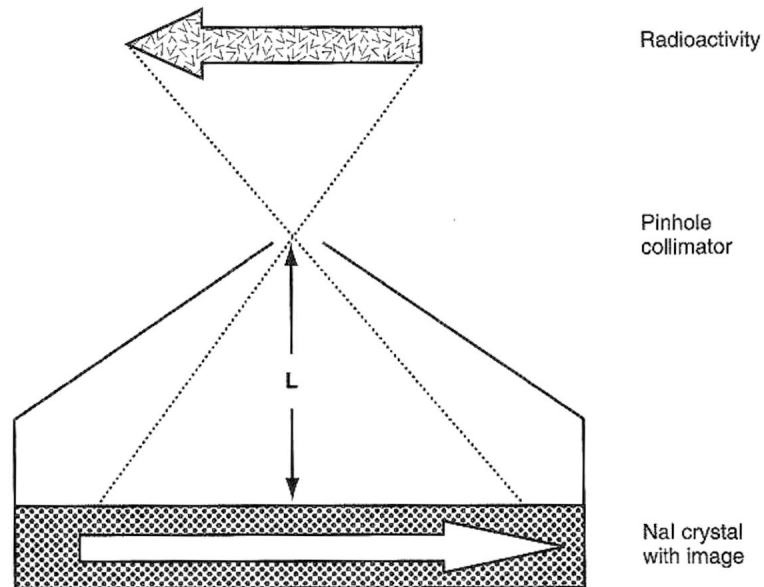
- **Divergent collimators** are used to minify the image by means of holes that cause the image to diverge from the view of the NaI crystal to points in front of the collimator.



- **Pinhole collimators** can either magnify or minify the source object, depending on the distance of the source object from the collimator. If the distance is  $>L$  (focal length), the image is minified. If the distance is  $<L$ , the image



is magnified. The left and right are reversed. This collimator is useful for higher energy gammas when the outer shell of the pinhole can be made thicker. It is also used to enlarge small parts of the anatomy by different amounts.



- The efficiency of parallel hole collimators decreases with thicker lead septa ( $t$ ) between holes. However, thick septa are needed for high-energy photons.
- The efficiency of parallel hole collimators decreases as the length of holes ( $L$ ) increases. Long holes are needed for better spatial resolution.
- The efficiency of parallel hole collimators increases as the diameter ( $d$ ) of the holes increases. Wide holes result in worse spatial resolution.
- **Sensitivity ( $G$ , efficiency) for a parallel hole collimator** with a point source is

$$G_{pt} = \text{sensitivity} = d^4 / [4\pi L^2 (d + t)^2]$$

- Sensitivity for a parallel hole collimator with a plane source is

$$G_{plane} = \text{sensitivity} = Nd^4 / [4\pi L^2]$$

where  $N$  = number of holes.

- The **resolution of a parallel hole collimator** degrades with distance ( $X$ ) away from the collimator face. The blur is measured by the **FWHM** counts for a point source.

$$\text{FWHM} = [d(X + L)] / L$$

where  $d$  and  $L$  were defined previously.

**3. Problems that degrade the quality** of scintillation camera images include the following:

- Motion related to long acquisition times
- Counting of scattered gamma photons
- Displacement away from the collimator
- Septal penetration by high-energy gammas
- Light and photon scattering in the NaI crystal
- Collimator limitations



- Tissue attenuation that decreases count rates
  - Superimposition of various sources in the body
  - Energy uncertainty related to 20% PHA windows
  - NaI crystal defects
  - Too few counts per image, which results in quantum mottle and limits the ability to see “hot” and “cold” areas in the image
4. **Uniformity** is measured in two different ways.
- **Intrinsic uniformity** requires removal of the collimator and the placement of a Tc-99m point source far from the crystal. It measures only crystal uniformity.
  - **Extrinsic uniformity** places a flood source (Tc-99m in water or a Co-57 plastic disk) directly on the collimator. It measures the uniformity of both the crystal and the collimator.
  - Uniformity measurements should accumulate at least 1 million counts to limit statistical variation.
  - Without correction, uniformity should be better than  $\pm 10\%$ . With correction, uniformity can be better than  $\pm 5\%$ .
5. Quality control (QC) tests for scintillation cameras include the following:
- Uniformity
  - Spatial resolution using bar patterns and a flood source
  - Spatial distortion using uniform hole patterns and a flood source
  - Centering of PHA around the photopeak
  - Dead time measurements of count rate loss
6. SPECT (single photon emission computed tomography) uses one or more scintillation cameras, which rotate around the body and reconstruct the data to form tomographic images.
- Careful balance and mechanical centering of the various detectors are required.
  - Transmission measurements with an external source are required to correct for tissue attenuation to quantify amounts of activity.

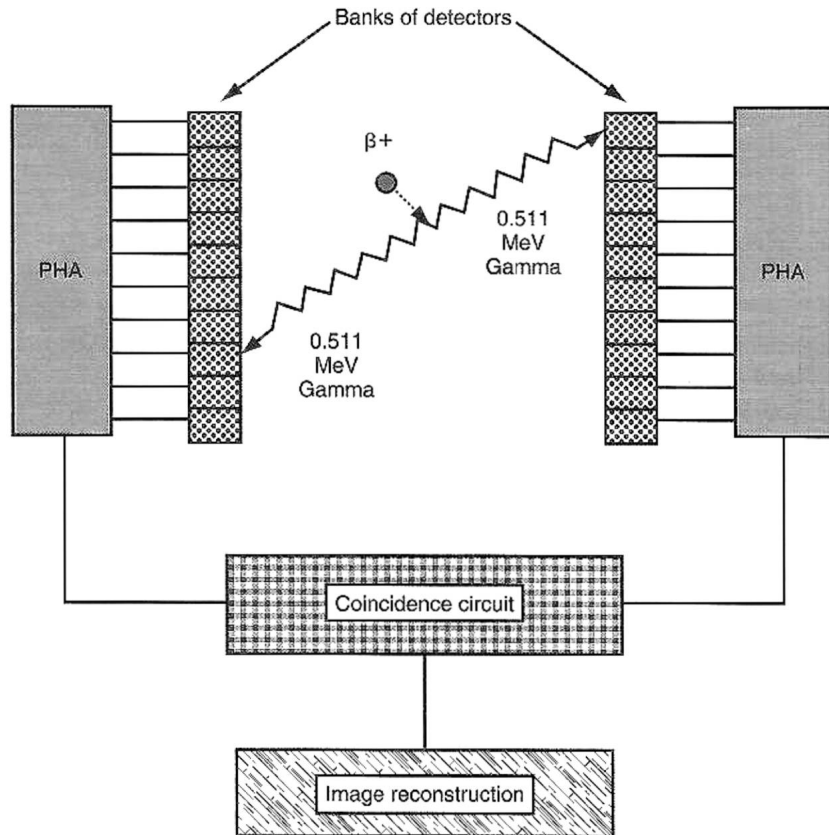
## G. Positron Emission Tomography (PET) Units

1. PET uses cyclotron-produced short-half-life radioisotopes that emit positrons ( $\beta^+$ ). The major positron emitters are listed in the table.

POSITRON EMITTER	HALF-LIFE (MINUTES)	AVERAGE $\beta^+$ ENERGY (MeV)
O-16	2	0.72
N-13	10	0.49
C-11	20	0.38
F-18	110	0.28

2. The positrons lose energy by ionization as they travel through tissue. In the process, they slow down. Because the positron is an antiparticle, it eventually combines with an electron (after it slows down), and the two particles are annihilated. As matter is destroyed, two 0.511-MeV photons are produced that travel in nearly 180-degree opposite directions.

3. PET scanners use banks of detectors to measure two nearly simultaneous events (coincidence circuits) with energies of 0.511 MeV (with PHA) to discern a positron annihilation. The annihilation is on a straight line between the two detectors recording simultaneous 0.511-MeV events.



4. To quantify tissue attenuation, corrections must be determined with a separate external ring source.
5. Factors that affect image quality include the following:
- The positron travels about 1 to 4 mm before the annihilation occurs, which results in malpositioning of the emission.
  - The two 0.511-MeV photons are not exactly 180 degrees apart, which causes slight malpositioning of the emissions.
  - False coincidences occur with one photon from two different decays occurring at the same time.
  - Detector size and collimator size introduce some uncertainty in positioning.
  - Uncertainty in PHA windows allows small-angle scattered photons to be accepted.
6. Advantages of PET scanners include the following:
- Chemical tracers can be formed with atoms typically found in tissue such as carbon, nitrogen, and oxygen.
  - High-energy photons are not attenuated much by body anatomy.
  - Short half-life means activity in patients decays rapidly.

## H. Nuclear Medicine Statistics



1. **Mean ( $\bar{X}$ )** is the average of a group of measurements ( $X_i$ ).

$$\bar{X} = (\sum X_i) / N$$

where  $N$  = number of measurements.

2. **Standard deviation ( $\sigma$ )** is approximated by the square root of the mean value.

$$1\sigma \cong (\bar{X})^{0.5}$$

3. **Variance** is equal to the standard deviation squared.

$$\text{Variance} = \sigma^2$$

4. **Confidence interval** is the percentage of the measurements that fall within plus or minus the indicated value above or below the mean value of the measurements.

VALUE AROUND MEAN	CONFIDENCE INTERVAL (%)
$\pm 1\sigma$	68.3
$\pm 2\sigma$	95.5
$\pm 3\sigma$	99.7

5. The standard deviation for count rates is different.

$$1\sigma_{\text{RATE}} = \sqrt{R/T}$$

where  $R$  = count rate and  $T$  = counting time.

6. **Net counts (or count rate)** are source plus background minus background.

7. Standard deviation for the sum or difference of two sets of counts is given as

$$1\sigma_{\text{COUNTS}} = \sqrt{(N_1) + (N_2)}$$

8. Standard deviation for the sum of or difference in count rates is given as

$$1\sigma_{\text{RATE}} = \sqrt{(R_1/T_1) + (R_2/T_2)}$$

## I. Questions

- 21-1. The Tc-99m radioisotope generator is an example of the physics principle of \_\_\_\_\_.

(a) Cascade process    (b) Retrograde flow    (c) Transient equilibrium  
(d) Secular equilibrium    (e) Nuclear propagation

- 21-2. Emission from an isomeric decay can include all of the following, *except* \_\_\_\_\_.

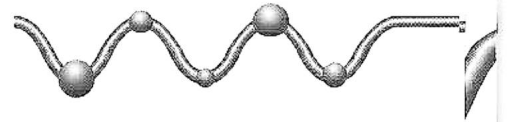
(a) X-ray photons    (b) Gamma ray photons  
(c) Internal conversion electrons    (d) Auger electrons    (e) Beta particles

- 21-3. The amount of Mo-99 "breakthrough" allowed per mCi of Tc-99m eluant is \_\_\_\_\_  $\mu\text{Ci}$ .

(a) 0.015    (b) 0.15    (c) 1.5    (d) 15.0    (e) 150



- 21-4.** A 500-mCi Tc-99m radioisotope generator is not used for 137 hours. Then it is eluted. Twelve hours later, the generator is eluted a second time. The two elutions are combined. The total activity in the combined two elutions is about \_\_\_\_\_ mCi.  
 (a) 31 (b) 67 (c) 87 (d) 111 (e) 186
- 21-5.** A decay process that occurs in nuclei that have excess protons and is always followed by the emission of characteristic x-rays is called \_\_\_\_\_.  
 (a) Beta minus (b) Beta plus (c) Isomeric transition  
 (d) Electron capture (e) Alpha emission
- 21-6.** A decay process that only reduces the excess energy in the nucleus is called \_\_\_\_\_.  
 (a) Beta minus (b) Beta plus (c) Isomeric transition  
 (d) Electron capture (e) Alpha emission
- 21-7.** A decay process that occurs in nuclei that have excess neutrons is called \_\_\_\_\_.  
 (a) Beta minus (b) Beta plus (c) Isomeric transition  
 (d) Electron capture (e) Alpha emission
- 21-8.** A decay process that occurs primarily in nuclei with  $Z > 80$ , such as radium, is called \_\_\_\_\_.  
 (a) Beta minus (b) Beta plus (c) Isomeric transition  
 (d) Electron capture (e) Alpha emission
- 21-9.** Nuclei with an excess number of neutrons are usually created by radiation bombardment in a \_\_\_\_\_.  
 (a) Linear accelerator (b) Van de Graaff generator (c) Cyclotron  
 (d) Nuclear reactor (e) Betatron
- 21-10.** The radiation dose to a critical organ from a beta-emitting radiopharmaceutical increases for greater amounts of the following factors, *except* \_\_\_\_\_.  
 (a) Organ mass (b) Effective half-life (c) Photon energy  
 (d) Biodistribution (e) Injected activity
- 21-11.** The combination of physical half-life ( $T_p$ ) and biologic half-life that results in the greater critical organ dose is  $T_p =$  \_\_\_\_\_ hours and  $T_B =$  \_\_\_\_\_ hours.  
 (a) 6, 48 (b) 110, 5 (c) 4, 100 (d) 7, 7 (e) 80, 7
- 21-12.** The number of gamma photons produced per second by a 10-Bq source of Co-60 is \_\_\_\_\_, and for Tc-99m it is \_\_\_\_\_.  
 (a) 5, 5 (b) 10, 5 (c) 20, 9 (d) 10, 20 (e) 10, 10
- 21-13.** Emissions from a positron decay include \_\_\_\_\_.  
 (a) Alpha particles (b) Protons (c) Neutrinos  
 (d) Characteristic x-rays (e) Neutrons
- 21-14.** When  ${}^7_7\text{N}^{13}$  decays by means of positron emission, it produces an atom of \_\_\_\_\_.  
 (a)  ${}^8_8\text{O}^{15}$  (b)  ${}^6_6\text{C}^{13}$  (c)  ${}^7_7\text{N}^{12}$  (d)  ${}^9_9\text{F}^{14}$  (e)  ${}^5_5\text{B}^{11}$
- 21-15.** Nuclei that undergo electron capture have \_\_\_\_\_.  
 (a) Excess protons (b) Excess neutrons (c)  $Z > 80$   
 (d) Excess electrons (e) High mass numbers
- 21-16.** For gamma emissions from a radiopharmaceutical, the radiation dose to the spleen from a source in the liver increases with \_\_\_\_\_.



- (a) Higher photon energy    (b) Lower photon energy    (c) Short half-life  
(d) Low S value    (e) Low accumulated activity
- 21-17.** The device on a scintillation camera that is used to reject scattered photons is called a \_\_\_\_\_.
- (a) PHA    (b) TOF    (c) PBL    (d) Collimator    (e) Grid
- 21-18.** The energy resolution of a radiation detector is measured by the \_\_\_\_\_.
- (a) MCA    (b) CCD    (c) CNR    (d) FWHM    (e) EMF
- 21-19.** A photon spectrum of a Tc-99m source is recorded with an NaI scintillation detector and a spectrum analyzer. A peak in the spectrum found at 110 keV is called the \_\_\_\_\_.
- (a) Compton edge    (b) Iodine x-ray peak    (c) Coincidence peak  
(d) Lead x-ray peak    (e) Iodine escape peak
- 21-20.** An artifact in a scintillation camera image that appears as a “cold spot” could be due to all of the following factors, *except* \_\_\_\_\_.
- (a) Off-center PHA    (b) Nonuniform biodistribution    (c) Defective PMT  
(d) Metal in the FoV    (e) NaI crystal defect
- 21-21.** The type of radiation detector that is often used as a survey instrument to locate small amounts of radioactivity contamination without providing measurements related to energy deposited is a(n) \_\_\_\_\_.
- (a) Ionization chamber    (b) GeLi detector    (c) Liquid scintillation detector  
(d) GM counter    (e) TLD
- 21-22.** The type of radiation detector that uses coincidence circuits and refrigeration systems to detect low-energy charged particles is a(n) \_\_\_\_\_.
- (a) NaI well counter    (b) Bonner sphere meter  
(c) Liquid scintillation detector    (d) Cutie Pie survey meter  
(e) MOSFET device
- 21-23.** The typical spatial resolution of scintillation cameras is limited by all of the following factors, *except* \_\_\_\_\_.
- (a) Collimator design    (b) Distance from collimator  
(c) Light spread in scintillation crystal    (d) Photon scatter in the patient  
(e) Pixel size
- 21-24.** The loss of counts due to high radioisotope activity that affects the ability of the detector system to process data at high speeds is called \_\_\_\_\_.
- (a) Dead time    (b) Vignetting    (c) Pulse pile-up    (d) Quenching  
(e) Recombination
- 21-25.** All of the following are positron emitters used with PET scanners, *except* \_\_\_\_\_.
- (a)  ${}^9_5\text{B}$     (b)  ${}^{11}_6\text{C}$     (c)  ${}^{13}_7\text{N}$     (d)  ${}^{15}_8\text{O}$     (e)  ${}^{18}_9\text{F}$
- 21-26.** Quality control tests for scintillation cameras include all of the following, *except* \_\_\_\_\_.
- (a) Uniformity    (b) Spatial resolution    (c) Coincidence timing  
(d) Spatial distortion    (e) PHA centering
- 21-27.** The background count rate is 16 cpm, and the source plus background count rate is 20 cpm. The data must be accumulated for \_\_\_\_\_ minutes so that the net count rate is different from the background with a confidence level of 95%.
- (a) 3    (b) 6    (c) 9    (d) 12    (e) 16
- 21-28.** The type of scintillation camera collimator that can only magnify the portion of the anatomy in the image is a \_\_\_\_\_ collimator.



- (a) Parallel hole    (b) Convergent    (c) Divergent    (d) Pinhole  
(e) GAP

**21-29.** To do quantitative activity measurements, SPECT and PET scanners must correct for \_\_\_\_\_.

- (a) PHA    (b) Attenuation    (c) Unsharpness    (d) Scatter  
(e) Conspicuity

**21-30.** The maximum critical organ dose for most nuclear medicine studies is about \_\_\_\_\_ cGy, and the whole body dose is usually about \_\_\_\_\_ cGy.

- (a) 5, 0.2    (b) 1, 0.01    (c) 0.2, 2    (d) 0.5, 5    (e) 10, 5

## J. Answers

**21-1.** Answer = (c). Cascade decay is a process in which one photon emission is immediately followed by a second photon emission. Thus, for one decay, two photons are emitted. Retrograde flow is usually applied to anatomic functions when a substance travels in the opposite direction to normal flow. Secular equilibrium occurs in a generator when the parent's half-life is much, much greater (>100) than the daughter's half-life. Thus, for short periods of time, the daughter and the parent stay in equilibrium with approximately equal activity and negligible reduction of activity related to the long half-life of the parent. Nuclear propagation is a term not normally used in nuclear medicine.

**21-2.** Answer = (e). In an isomeric transition, a gamma photon is released from the nucleus. It may then exit through the orbital electrons surrounding the nucleus. Alternatively, the photon could interact with an inner shell electron and disappear, transferring its energy to the electron that is ejected (internal conversion electron). The vacancy in the inner shell electrons is then filled by rearrangement of the remaining electrons, which produces a characteristic x-ray. Sometimes the characteristic x-ray is not emitted because it interacts with an outer shell electron and ejects it (Auger electron). Beta (either plus or minus) refers to an electron that originates in the nucleus. An electron from an orbital shell is just an electron, *not* a beta.

**21-3.** Answer = (c). See note in this chapter (B5). Mo-99 must be limited because it emits beta particles. Emissions with charged particles result in a considerable radiation dose to the patient.

**21-4.** Answer = (d). After 137 hours, the Mo-99 has undergone a reduction in activity by two half-lives. Hence, the 500 mCi is reduced to one fourth of its original amount, or 125 mCi. The Tc-99m and Mo-99 activities are at equilibrium, so that 125 mCi is eluted. Now, the Tc-99m decays at a rate determined by its half-life of 6 hours. After 12 hours, the activity of the first elution is reduced by another factor of one fourth to 31 mCi. The activity of the Mo-99 at 149 hours (137 + 12 hours) is 107 mCi. However, after an elution, secular equilibrium is not reached. At 12 hours after elution, the Tc-99m is only  $[(1.0 - (0.5)^2)] = 0.75$  of the parent activity. Therefore the second elution yields  $0.75 \times 107 \text{ mCi} = 80.0$ . So the total activity is  $80 + 31 = 111 \text{ mCi}$ .

**21-5.** Answer = (d). For nuclei with excess protons, both electron capture and positron emissions can occur. However, only electron capture causes a vacancy in the outer shell electrons, which then rearrange and produce characteristic x-rays.

**21-6.** Answer = (c). See note in this chapter (A7).

**21-7.** Answer = (a). See note in this chapter (A7).

**21-8.** Answer = (e). See note in this chapter (A7).



- 21-9.** Answer = (d). To produce nuclei with excess neutrons, the atoms with stable nuclei must be bombarded with neutrons. Of the radiation sources listed, only the nuclear reactor produces significant numbers of neutrons.
- 21-10.** Answer = (a). As the organ mass increases, the radioactivity and radiation dose are distributed over more tissue. Thus, the radiation dose is reduced with more tissue. Similarly, for pediatric patients, the organ sizes are smaller and the radiation doses are greater for injected activity that is the same as that used in adults.
- 21-11.** Answer = (d). The greatest effective half-life results in the greatest critical organ dose. For significantly different physical and biologic half-lives, the effective half-life is slightly less than the smallest value. For nearly equal physical and biological half-lives, the effective half-life is about 0.5 times either half-life. The effective half-lives for the data listed in the answers, in order, are 5.3, 4.8, 3.9, 3.5, and 6.4 hours.
- 21-12.** Answer = (c). Co-60 has a cascade decay in which two photons are emitted per decay. For Tc-99m, 10% of the emitted photons undergo internal conversion. Hence, only 0.9 photons are emitted per decay. 1 Bq is one decay per second.
- 21-13.** Answer = (c). If a real beta is emitted ( $\beta^-$  = electron), an antineutrino is also released. If an antiparticle ( $\beta^+$  = positron) is emitted, a real neutrino is emitted.
- 21-14.** Answer = (b). For positron emission, the atomic number decreases by one and the number of neutrons increases by one. The total number of nuclei (neutrons plus protons) remains the same.
- 21-15.** Answer = (a). See notes in this chapter (A1 and A7).
- 21-16.** Answer = (a). Lower energy photons cannot penetrate the tissue of the liver and escape to impinge on the spleen. The radiation dose to the spleen is less for shorter half-lives, a lower S value, and less administered activity. The higher photon energy allows the radiation to penetrate the liver and irradiate the spleen.
- 21-17.** Answer = (a). Scattered photons have less energy, and the pulse height analyzer (PHA) determines the energy deposited in the crystal. TOF is "time of flight," which can be used on PET scanners to partially locate events. PBL is "positive beam limitation," which is the automatic collimation system of x-ray units. Collimators are for the proper placement of photons related to a specific anatomic location, not scatter rejection. Grids are found on x-ray systems, and they are not part of scintillation cameras.
- 21-18.** Answers = (d). FWHM is full width at half maximum, which is the width of the measured energy peak. MCA is a multichannel analyzer, which is a series of PHAs that can measure an entire photon spectrum. CCD is a charge-coupled device, which is a solid-state television camera. CNR is the contrast-to-noise ratio, which is a measure of image quality. EMF is electromagnetic force, which is used to describe radiofrequency interference.
- 21-19.** Answer = (e). The iodine escape peak is created when a 140-keV Tc-99m photon undergoes a photoelectric interaction in the NaI crystal, depositing all its energy. However, an iodine characteristic x-ray is produced by the rearrangement of orbital x-rays to fill the vacancy created by the photoelectric interaction in the crystal. If the x-ray escapes, the deposited energy is 140 keV minus 33 keV (of the iodine characteristic x-ray); the energy deposited is about 110 keV. If only the 33-keV iodine x-ray is deposited in the crystal, it is called the iodine x-ray peak. The Compton edge occurs when a 180-degree scatter photon deposits its energy into the crystal. This energy is equal to  $2\alpha E_0 / (1 + 2\alpha)$ ; it is equal to 50 keV for Tc-99m and 478 keV for Cs-137. A coincidence peak occurs when two photons deposit all their energy in the crystal at the same time so that it looks like there is a single photon with double the energy. Characteristic x-rays of lead occur at 80 to 88 keV and are sometimes counted in a peak.



- 21-20.** Answer = (b). A nonuniform biodistribution can cause cold spots. However, these cold spots are real and are not artifacts. A PHA that is off center would not detect real events. A failed PMT would not detect any events, causing a cold spot. Metal-like jewelry would attenuate gamma photons, causing cold spots. A crystal defect such as a crack would also cause cold spots.
- 21-21.** Answer = (d). Ionization chambers measure a charge related to the energy deposited in the detector. Germanium-lithium (GeLi) solid-state detectors are used to obtain good energy discrimination to identify one or more radioisotopes by means of the energy of their gamma emissions. Liquid scintillation detectors are used for low-energy particle detection in fluids such as urine and blood. TLDs are thermoluminescent dosimeters used for personnel dosimetry.
- 21-22.** Answer = (c). Liquid scintillation systems measure low-energy, charged particle emissions, usually in a liquid such as urine or blood. NaI well counters are used to measure samples with gamma ray emissions, as in radioimmunoassay (RIA) studies and wipe tests. Bonner spheres are used for neutron detection. Cutie Pie survey meters are used for area surveys and are a type of ionization chamber. MOSFET stands for metal oxide silicon field effect transistors, which are solid-state radiation detectors. They measure directly charges created within the silicon chips.
- 21-23.** Answer = (e). Pixel size in a scintillation camera is the FoV (10 to 12 inch) divided by the matrix (128 to 256), or 1.0 to 2.5 mm. Spatial resolution in scintillation cameras is about 7.5 mm, which is bigger than the pixel size. Light spread in the crystal is measured by numerous PMTs to locate the interaction of the photons in the crystal. Reflections of light in the scintillation crystal cause uncertainty in the event position. Large collimator holes improve sensitivity, but they reduce spatial resolution. Spatial resolution degrades as the source is moved farther from the camera. Photons scattered through small angles would be detected as undeflected photons because of the 20% energy width of the PHA. Thus, these small-angle scattered photons are not positioned properly.
- 21-24.** Answer = (a). Dead time is the period after detection of a radiation event during which a detector cannot sense another event. Vignetting occurs in image intensifiers; the effect is that the center of the image is brighter than the edges. Pulse pile-up occurs at the edge of a scintillation camera because there are no PMTs outside the edge of the crystal to position events properly. Quenching can occur in liquid scintillation detectors or GM counters; it is the loss of counts related to impurities in the detector that absorb the ionizations. Recombination is loss of counts in gas detectors because of low applied voltages that are insufficient to prevent the ion pairs from recombining.
- 21-25.** Answer = (a). See the list of PET radioisotopes in this chapter (G1).
- 21-26.** Answer = (c). Scintillation cameras do not use coincidence circuits. Intrinsic uniformity and extrinsic uniformity are major QC tests to prevent false hot and cold spots. Bar patterns are used to assess spatial resolution. Distortion is checked with use of uniform hole patterns. PHA centering is necessary to prevent artificial hot or cold spots.
- 21-27.** Answer = (c). The standard deviation of the result of subtraction of two count rates is equal to  $[(R_1/T) + (R_2/T)]^{0.5}$ . For 95% confidence regarding the difference between the source plus background minus the background (net count rate), the difference must be at least twice the standard deviation. If both sides of the equation are squared and solved for time (T),  $T = [4(R_1 + R_2)]/[R_1 - R_2]^2 = [4(20 + 16)]/[20 - 16]^2 = 4(36)/16 = 9$  minutes.
- 21-28.** Answer = (b). A parallel hole collimator and a general all purpose (GAP) collimator are the same, and both keep the object and image size the same. A divergent collimator minifies the image. A pinhole collimator can either magnify or minify the image depending on the distance from the source object.

- 21-29.** Answer = (b). Correction for photon attenuation is necessary to obtain the initial number of photons emitted toward the detectors. PHA is used to eliminate the scattered photons from the counts. Unsharpness is blur that affects spatial resolution; it does not affect the count rate. Scatter is eliminated by the PHA. It is part of the attenuation that should not be included in quantification studies. Conspicuity is an term that indicates the relative contrast between the object and the background.
- 21-30.** Answer = (a). Because most nuclear medicine images are limited by the photon statistics (the quantum mottle of too few photons), most studies administer sufficient activity to limit the critical organ dose to less than 5 cGy (rad). Because the radiation levels to the remaining organs are much lower, the average dose (or whole body dose) is usually 5% or less of the critical organ dose.

