Chapter 10: Non-imaging detectors and counters

Slide set of 87 slides based on the chapter authored by
P.B. ZANZONICO
of the IAEA publication (ISBN 78–92–0–143810–2):
Nuclear Medicine Physics:
A Handbook for Teachers and Students

Objective: To familiarize the student with the fundamental concepts of electronics related to nuclear medicine imaging devices

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CHAPTER 10 TABLE OF CONTENTS

10.1. INTRODUCTION

- Historically, nuclear medicine has been largely an imaging based specialty, employing such diverse and increasingly sophisticated modalities as:
  - Rectilinear scanning
  - (Planar) gamma camera imaging
  - Single photon emission computed tomography (SPECT)
  - Positron emission tomography (PET)

10.1. INTRODUCTION

☐ Non-imaging radiation detection, however, remains an essential component of nuclear medicine, including:

- Survey meters
- Dose calibrators
- Well counters
- Intra-operative probes
- Organ uptake probes

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

- Radiation detectors encountered in nuclear medicine may generally be characterized as either
  - scintillation
    - Visible light is produced as radiation excites atoms of a crystal
    - Light is converted to an electronic signal/pulse
    - Pulse is amplified by a PMT
    - High voltage (500–1500 V)
  - ionization detectors
    - Free electrons are produced as radiation ionizes a stopping material
    - Happens within a sensitive volume
    - Electrons electrostatically collected by a bias voltage (10–500 V) produce an electron signal

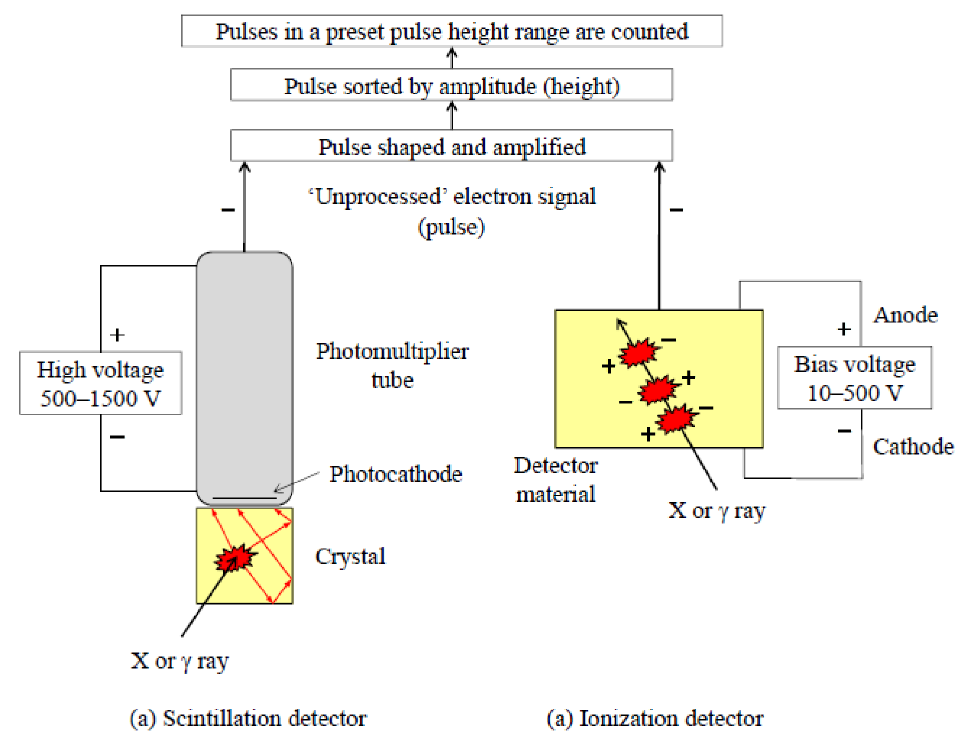
10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

- For both detector types, the ‘unprocessed’ signal is then shaped and amplified

- For some types of detector, the resulting pulses are sorted by their amplitude (or pulse height), which is related to the X-ray or γ-ray energy absorbed in the detector

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

- Basic design and operating principles of
  a) Scintillation
  b) Ionization detectors



(a) Scintillation detector (a) Ionization detector

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.1. Ionization detectors

- ☐ Detector materials
  - Most commonly gaseous
  - Known as gas filled detectors
    - Most widely encountered ones in nuclear medicine are
      - Dose calibrators
      - Geiger counters

      (Difference is the bias voltage magnitude between anode & cathode)
  - Solid state ionization detectors also exist

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.1. Ionization detectors

- ❑ V < 300 V, Recombination region
  - Created ion pairs may recombine
    - Prevents some electrons from reaching the anode
    - Yields an artefactually low signal

- ❑ At V = 300 V
  - All primary electrons are collected at the anode
  - Detector signal is maximized

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.1. Ionization detectors

- ❑ V = 300 – 600 V, Ionization chamber region
  - Signal does not increase
  - There are no additional primary electrons to collect
  - Overall signal is equivalent to the number of primary electrons
  - Proportional to the energy of the incident radiation

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.1. Ionization detectors

- V = 600 – 900 V, Proportional counter region
  - Large electrostatic force of attraction of the anode
    - Free electrons accelerate towards the anode
  - Gain speeds high enough to eject additional (secondary) orbital electrons
    - Contribute to an increasing overall signal
  - Higher the voltage means:
    - More energetic the electrons
    - More secondary electrons added to the overall signal
  - Number of electrons in the overall signal is proportional to energy of the incident radiation

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.1. Ionization detectors

- ❑ V = 900 – 1200 V, Geiger–Müller region
  - Free electrons (primary and secondary) are accelerated
  - Speeds are very high
  - Tertiary electrons are ejected from the anode surface
    - They are accelerated back to the anode surface
    - Eject even more electrons
    - Electron ‘cloud’ over the anode is formed
      - Charge amount of the electron cloud is independent of the number of electrons initiating its formation
    - Yields a constant overall signal even with more bias increase
  - Signals are independent of the incident radiation energy

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

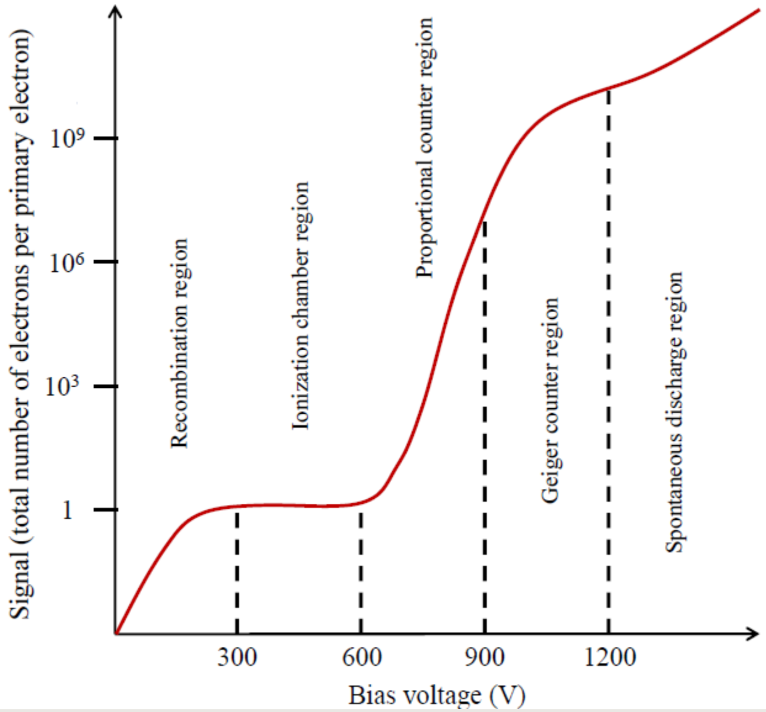
10.2.1. Ionization detectors

- V > 1200 V, Spontaneous discharge region
  - Atoms ionized spontaneously without incident radiation
  - Artefactual signal produced

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.1. Ionization detectors

- ❑ The signal (expressed as the amplification factor, that is, the total number of electrons per primary electron produced in the detector material) as a function of the bias voltage for gas filled ionization detectors



10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.1. Ionization detectors

- ☐ Other differences among different types of gas ionization detectors
  - Sealed *vs* unsealed sensitive volumes
    - Unsealed volumes contain only air at atmospheric pressure
      - Signal must be corrected for the difference between the temperature and pressure at which the detector was calibrated and the ambient conditions at the time of an actual measurement
        - Usually STP: 27°C and 760 mm Hg

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.1. Ionization detectors

- Sealed volumes
  - Use gases other than air (e.g. argon)
  - Gas may be pressurized
    - Provides higher stopping power
    - Provides higher sensitivity

- Different anode and cathode geometries
  - Parallel plates (in some ionization chambers)
  - Wire along the axis of a cylinder (used in Geiger counters)

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.1. Ionization detectors

❑ Ionization chambers are widely used in radiation therapy

- Used to calibrate the output of therapy units
- Used in nuclear medicine as dose calibrators
  - To assay radiopharmaceutical activities
- Relatively low sensitivity
  - Not a disadvantage because radiation intensities are typically rather large
- Response stability is an advantage as it allows the use of unconditioned AC electrical power

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.1. Ionization detectors

☐ Proportional counters

- Need a stable bias voltage
  - ➢ specialized power supplies
- Restricted to research applications (e.g. in radiobiology)
  - Need higher sensitivity
  - Need capability of energy discrimination
- Often employ an unsealed, gas flow-through sensitive volume

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10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.1. Ionization detectors

- ❑ Geiger counters
  - High sensitivity and stability with respect to voltage
    - Can use a portable power supply such as an ordinary battery
  - Widely used as survey meters (sensitivity is critical)
    - To measure ambient radiation levels
    - To detect radioactive contamination
  - Sealed sensitive volumes
    - Don’t need temperature–pressure corrections

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.1. Ionization detectors

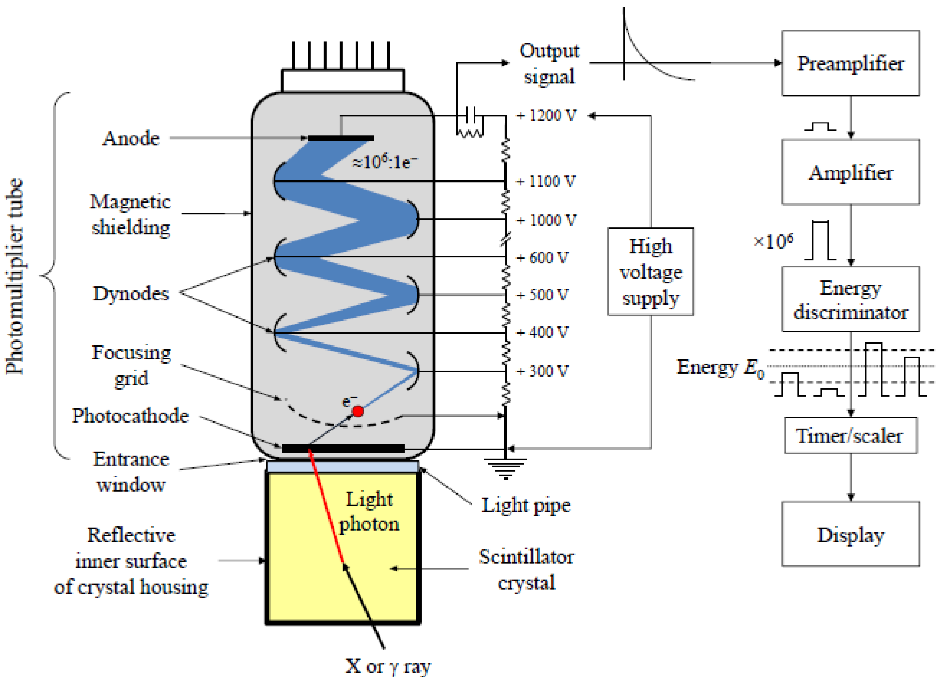
- The functional properties & applications of the various types of ionization are largely dictated by their respective bias voltage dependent signal

	Ionization detector	**Proportional counter**	**Geiger counter**
Bias voltage operating range	300–600 V	600–900 V	900–1200 V
Response stable with respect to voltage?[a]	Yes	No	Yes
Sensitivity[b]	Low	Intermediate	High
Capable of energy discrimination?[c]	Yes	Yes	No
Applications	Dose calibrator	Research	Survey meter

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.2. Scintillation detectors

- Scintillation detectors
  - Most commonly a crystalline solid such as
    - Thallium-doped sodium iodide (NaI(Tl))
  - Radiation interacts with and deposits energy in a scintillator
  - Deposited radiation energy is converted to visible light
    - Emitted isotopically



10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.2. Scintillation detectors

❑ Scintillation detector structure

- Light-tight crystal housing
    - Inner surface coated with reflective material
        - Light emitted towards crystal’s sides and front of the of the crystal are reflected back towards a PMT
    - Maximizes the amount of light collected
    - Maximizes overall sensitivity
- Photocathode
    - Coated on the inner surface of the PMT
    - Emits electrons

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.2. Scintillation detectors

- ☐ Scintillation detector structure
  - Focusing grid
    - Immediately beyond the photocathode
    - At relatively low +voltage , ~10 V
  - Light pipe
    - Between crystal back and PMT entrance window
    - Thin layer of transparent optical gel
    - Optically couples crystal to PMT
    - Maximizes transmission (>90%) of the light signal from the crystal into the PMT
    - At ground: 0 V

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.2. Scintillation detectors

- Scintillation detector structure
  - Dynodes
    - 1st dynode: attracts electrons passing through the focusing grid
      - Relatively large +voltage, ~300 V
      - Average of 3 electrons are ejected
    - 2nd dynode:
      - Even larger +voltage, ~400 V
      - Average of 3 e^- ’s ejected per incident one

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.2. Scintillation detectors

- ❑ Scintillation detector structure
  - Dynodes
    - PMT has 10–12 such dynodes (or stages)
      - Each ~100 V more + than the preceding
      - Entire PMT e^- amplification = 3^{10}–3^{12}
      - Output signal generated at last anode
        - Irregularly shaped
        - Shaped by a preamplifier
        - Further amplified into a logic pulse
          - can be further processed electronically

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.2. Scintillation detectors

☐ Pulse amplitudes (or ‘heights’) are proportional to:

- Number of electrons produced at photocathode
- Energy of the incident radiation

→ Energy discriminator

- Known as a pulse height analyser
- Sorts pulses by heights
- Pulses with height (i.e. energy) within the preset energy window are counted by a timer/scaler

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10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.2. Scintillation detectors

☐ Advantageous features of scintillation detectors include:

- High electron density, determined by:
  - ρ
  - Z_{eff}
    - More photoelectric than Compton interactions
    - Facilitates energy discrimination of photons
    - Maximizes
      - Stopping power (i.e. linear attenuation coefficient μ)
      - Sensitivity

10.2.2. Scintillation detectors

- Advantageous features of scintillation detectors include:
  - High light output
    - Reduces statistical uncertainty (noise)
    - Improves energy resolution & scatter rejection
  - Speed of light emission
    - Example: Important for PET

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.2. Scintillation detectors

- Other detector considerations include:
    - Transparency of the crystal to its own scintillations (i.e. minimal self-absorption)
    - Matching of the index of refraction η of the crystal to that of the photodetector
    - Matching of the scintillation wavelength to the light response of the photodetector
    - Minimal hygroscopic behaviour

10.2. OPERATING PRINCIPLES OF RADIATION DETECTORS

10.2.2. Scintillation detectors

- ☐ Most widely used scintillators in nuclear medicine include
  - NaI(Tl)
    - γ-cameras / SPECT systems
    - Well counters
    - Organ uptake probes
  - BGO
    - PET (higher stopping power for 511 keV)
  - LSO(Ce) or LSO
  - GSO(Ce) or GSO
  - CsI(Tl), CsI(Na), NaI(Tl), BGO and LSO have also been used in intra-operative probes

10.3. RADIATION DETECTOR PERFORMANCE

- ☐ Radiation detectors may be quantitatively characterized by many different performance parameters
  - Particularly for those detectors such as γ-cameras which localize (image) as well as count radiation

- ☐ For non-imaging radiation detectors and counters, the most important performance parameters are:
  - Sensitivity (or efficiency)
  - Energy resolution
  - Count rate performance (or ‘speed’)

10.3. RADIATION DETECTOR PERFORMANCE

10.3.1. Sensitivity

- ☐ Sensitivity (or efficiency)
  - Detected count rate per unit activity (e.g. cpm/MBq)
    - Highly dependent on:
      - Source–detector geometry
      - Intervening media

10.3. RADIATION DETECTOR PERFORMANCE

10.3.1. Sensitivity

- Geometric sensitivity
  - Fraction of emitted radiations which strike the detector
  - Directly proportional to the detector area
  - Inversely proportional to the square of source–detector distance (for point source)

10.3. RADIATION DETECTOR PERFORMANCE

10.3.1. Sensitivity

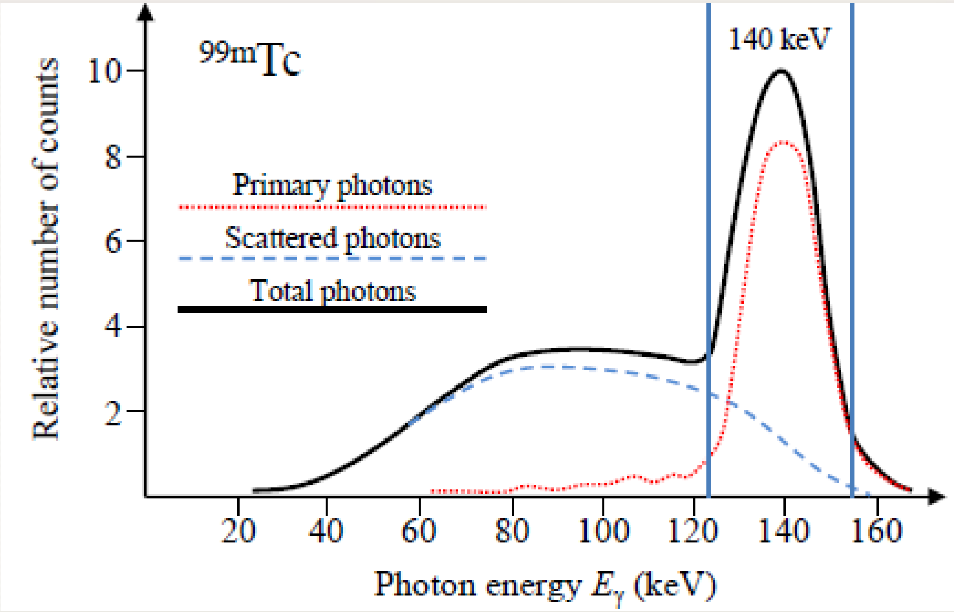
- Intrinsic sensitivity
  - Fraction of radiation striking the detector & stopped within the detector
  - Intrinsic sensitivity ↗ with:
    - Detector thickness
    - Z_{eff}
    - ρ
  - Intrinsic sensitivity ↘ with:
    - photon energy

      (Higher energy photons are more penetrating & are more likely to pass detector without interacting)

10.3. RADIATION DETECTOR PERFORMANCE

10.3.1. Sensitivity

- Characteristic X- & γ-rays are emitted with well-defined discrete energies
  - Output pulses from absorption will appear to originate over a range of energies (due to the relatively coarse energy resolution of the detector)

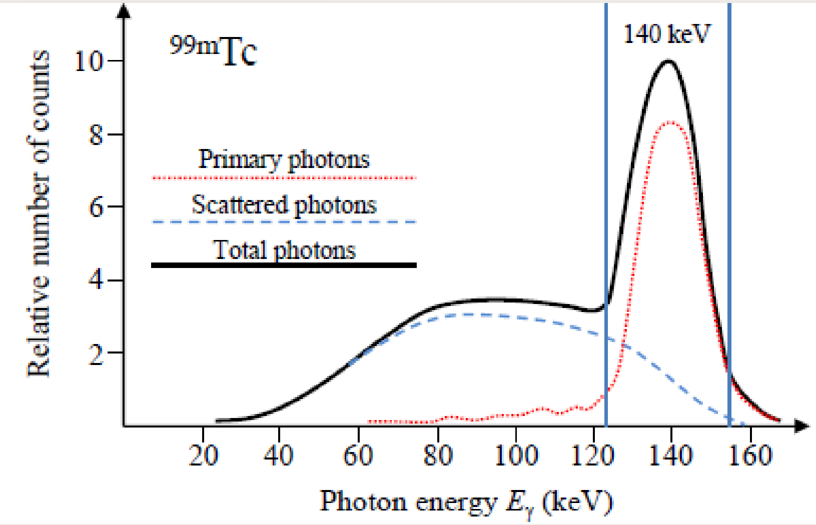


10.3. RADIATION DETECTOR PERFORMANCE

10.3.1. Sensitivity

- Many radiation detectors employ energy-selective counting
  - Using energy range (windows)
    - Scintillation detectors use a 20% window (E_γ ± 10%)

      e.g. 126–154 keV for 140 keV ^{99m}Tc γ-ray
    - Overall sensitivity appears to increase as E_γ window is widened
    - This results in acceptance of more scattered as well as primary (i.e. unscattered) radiations



10.3. RADIATION DETECTOR PERFORMANCE

10.3.1. Sensitivity

- ☐ Detector should be calibrated for each radionuclide & energy window used
  - Sensitivity S must be determined at installation & periodically after:

$$S = \frac{R_\mathrm{g} - R_\mathrm{b}}{\mathcal{A}_0 \mathrm{e}^{-\lambda \Delta t}}$$

R_g	is the gross (i.e. total) count rate (cpm) of the radionuclide source (RS);
R_b	is the background (BG), or blank, count rate (cpm);
$\mathcal{A}_0$	is the activity (MBq) of the radionuclide source at calibration;
λ	is the physical decay constant
Δt	is the time interval (in months or years depending on the half-life) between the calibration of the radionuclide and the current measurement

10.3. RADIATION DETECTOR PERFORMANCE

10.3.1. Sensitivity

- S is highly dependent on the source–detector counting geometry
  - Size of the source
  - Shape of the source
  - Source–detector distance
- Measured value applies exactly only for the geometry used for the measurement

10.3. RADIATION DETECTOR PERFORMANCE

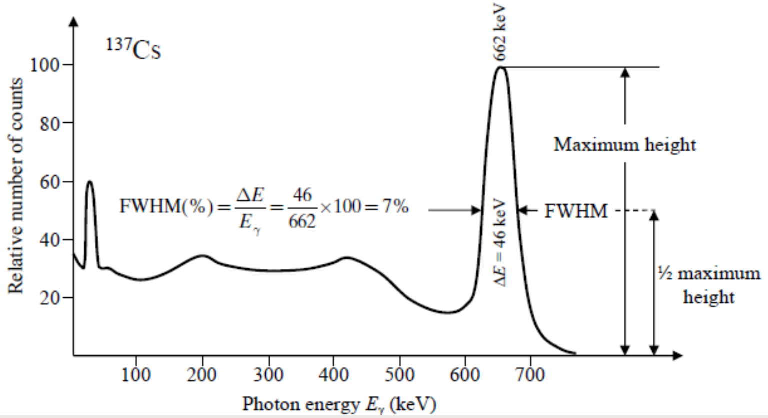
10.3.2. Energy resolution

☐ Energy resolution

- Ability to separate/discriminate different energies
- Given by the width of photopeak

$$\mathrm{FWHM}(\%) = \frac{\Delta E}{E_\lambda} \times 100\%$$

- Related to Poisson ‘noise’
  - Statistical uncertainty inherent in the detection process
- Important for scatter rejection with imaging detectors
  - Compton scattered radiation within source loses energy
  - Discrimination between scattered from primary radiations



10.3. RADIATION DETECTOR PERFORMANCE

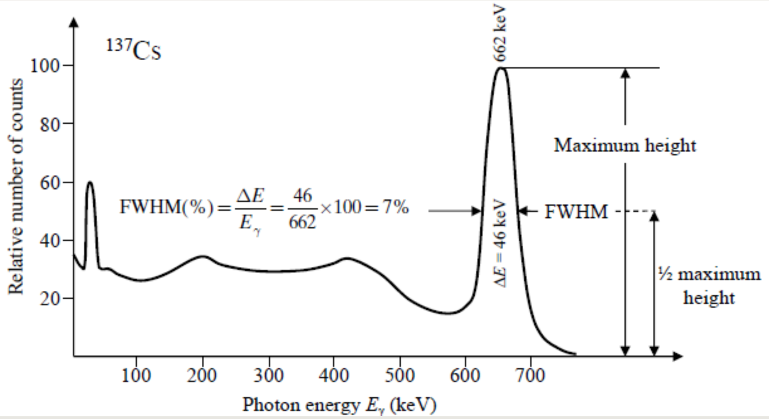
10.3.2. Energy resolution

☐ Energy resolution

- Scattered and primary radiations overlap (due to finite resolution)

$$\mathrm{FWHM}(\%) = \frac{\Delta E}{E_\lambda} \times 100\%$$

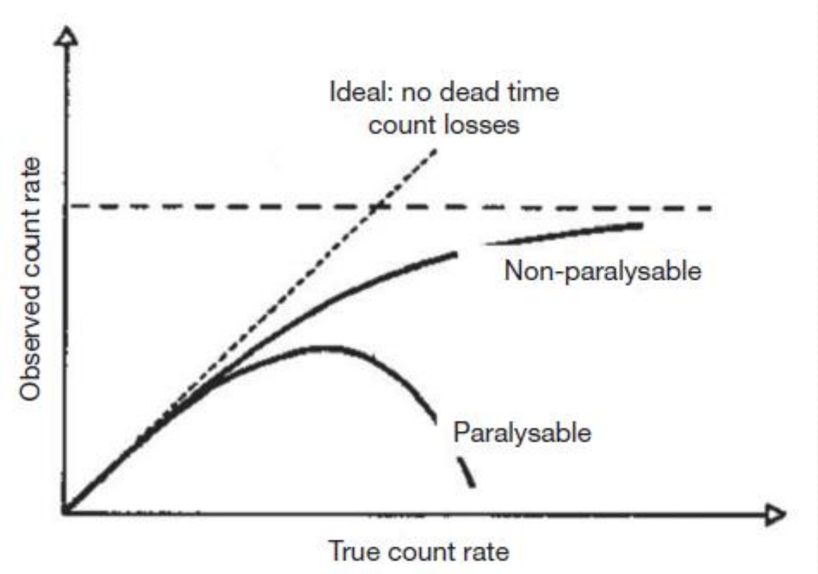
- Better resolution = narrower photopeak
  - Can better separate unscattered & scattered radiations
  - Can eliminate more scattered radiation counts
  - Fewer counts due to unscattered radiation are discarded



10.3. RADIATION DETECTOR PERFORMANCE

10.3.3. Count rate performance (‘speed’)

- Dead time for radiation detectors
  - Time required for a counting system to record an event
    - Additional events cannot be recorded
  - Typically $\tau \sim$ 5–10 μs for modern scintillation detectors
  - Associated count losses
    - Measured count rate is lower than actual count rate

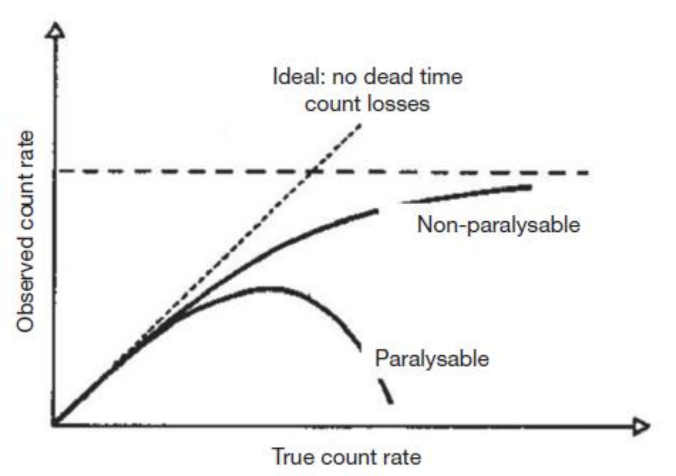


10.3. RADIATION DETECTOR PERFORMANCE

10.3.3. Count rate performance (‘speed’)

- Detectors are characterized as either
  - Non-paralysable
    - Dead-time due only to counted events
    - Example: Geiger counters (with quenching gas)
  - Paralysable
    - Dead-time due counted & not counted events
    - Example: well counters, γ cameras, PET scanners
  - Modern scintillators generally incorporate automated algorithms to correct for dead time

Observed *vs* true count rates for paralysable and non-paralysable radiation detectors



10.4. DETECTION AND COUNTING DEVICES

10.4.1. Survey meters

- Essential component of any radiation safety program
- Portable
- Battery operated
- Monitor ambient radiation levels

  exposure rates (C · kg^{-1}· h^{-1}) / count rates (e.g. in cpm)
- Solid state scintillation detectors
  - Employ non-air-equivalent crystal as the detection medium
  - Cannot measure exposure rates, only count rates

10.4. DETECTION AND COUNTING DEVICES

10.4.1. Survey meters

- Gas filled ionization detectors
  - ‘Cutie-pies’
    - Low sensitivity ionization chambers (i.e. low ΔV between anode & cathode)
    - Used with high fluxes of X-rays and γ-rays
    - Signal depends on the energy of the detected X-/γ-rays
    - Directly related to the exposure for all radionuclides

10.4. DETECTION AND COUNTING DEVICES

10.4.1. Survey meters

- Gas filled ionization detectors
  - ‘Geiger counters
    - Operated at high ΔV
    - High e^- amplification
    - High sensitivity
    - Suited for low level surveys (e.g. radioactive contamination)
    - Same amplitude signal for all energies
    - Calibrations apply only to the particular radionuclide(s) used to calibrate the counter

10.4. DETECTION AND COUNTING DEVICES

10.4.2. Dose calibrator

- Used for assaying radiopharmaceutical activities in:
  - vials
  - syringes
  - other small sources (e.g. brachytherapy sources)

- Pressurized gas filled ionization chamber
  - sealed sensitive volume
  - ‘well’-type geometry
    - High geometric efficiency
    - Overall sensitivity adequate for relatively high radiopharmaceutical activities

10.4. DETECTION AND COUNTING DEVICES

10.4.2. Dose calibrator

- Relatively low intrinsic sensitivity

- Adjust energy dependent responses via
  - Isotope-specific push-buttons
  - Potentiometer with isotope-specific settings
  - Accurate activity readouts (i.e. kBq or MBq) for any radioisotope

10.4. DETECTION AND COUNTING DEVICES

10.4.3. Well counter

- Used for high sensitivity counting of radioactive specimens
  - Blood
  - Urine
  - ‘Wipe testing’
- Use isotope specific calibration factor (cpm/MBq)
  - Provides results in terms of activity (e.g. MBq)

10.4. DETECTION AND COUNTING DEVICES

10.4.3. Well counter

- Most commonly NaI(Tl))
- Common design
  - Cylindrical scintillation crystal
  - Circular bore (well) for sample drilled part-way into the crystal backed by a PMT + electronics

10.4. DETECTION AND COUNTING DEVICES

10.4.3. Well counter

- Alternative design
  - ‘Through-hole’
  - Hole is drilled through the entire crystal
  - Facilitates sample exchange
  - Samples are centered lengthwise
  - More constant response for different volumes
  - Slightly higher sensitivity than well counters
- Crystal is surrounded by thick lead shielding in both designs
  - Minimizes ambient radiation background

10.4. DETECTION AND COUNTING DEVICES

10.4.3. Well counter

- Scintillation counters often have:
    - Multichannel analyzer for energy (i.e. isotope) selective counting
    - Automatic sample changer for multiple samples automated counting
- High intrinsic & geometric efficiencies
    - Resulting from thick crystal & well-type configuration
    - Extremely sensitive
    - Can reliably count activities ≤ ~100 kBq
    - At higher activities
        - Dead time losses may become prohibitive
        - The measured counts inaccurate

10.4. DETECTION AND COUNTING DEVICES

10.4.3. Well counter

- Integrated computer
  - To create & manage counting protocols
    - Specify isotope
    - Specify energy window
    - Specify counting interval
    - Manage sample handling
    - Apply background, decay, dead time & other corrections
  - Yield dead time-corrected net count rate decay corrected to the start of the current counting session

10.4. DETECTION AND COUNTING DEVICES

10.4.4. Intra-operative probes

- Small hand-held counting devices
- Widely used in cancer management
  - To expeditiously identify & localize sentinel lymph nodes
  - Reduce the need for more extensive surgery
  - Identify & localize visually occult disease

10.4. DETECTION AND COUNTING DEVICES

10.4.4. Intra-operative probes

- Almost exclusively for X-/γ-rays counting
  - Scintillation
    - Low cost
    - High sensitivity for medium-high energy γ ‘s
    - Disadvantages relative to semiconductor
      - bulkiness
      - poor energy resolution
      - Poor scatter rejection
  - Semiconductor (ionization)

10.4. DETECTION AND COUNTING DEVICES

10.4.4. Intra-operative probes

- Plastic scintillator β probes have also been developed
- Small (~10 cm) FOV intra-operative γ-cameras recently available
- Semiconductor based probes
    - Compact
    - More electrons per X/γ-ray stopped
        - ➢ Excellent energy resolution
        - ➢ Excellent scatter rejection
    - Thin (only ~1 mm)
        - Minimize structural imperfections which degrade energy resolution
        - Lower intrinsic sensitivity
    - Disadvantage
        - Limited thickness
        - Lower sensitivity

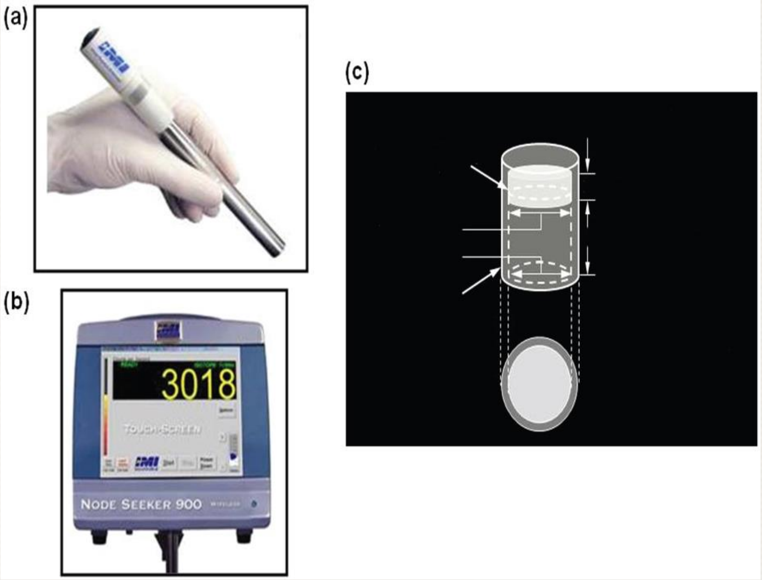
10.4. DETECTION AND COUNTING DEVICES

10.4.4. Intra-operative probes

- Typical intra-operative probe

  a) Hand-held detector

  b) Control and display unit
    - Displays current count rate
    - Often emits an audible signal, the tone of which is related to the count rate



  c) Detector & collimator assembly diagram
    - Detector (crystal) recessed from the collimator aperture

10.4. DETECTION AND COUNTING DEVICES

10.4.5. Organ uptake probe

- Almost exclusively for ‘thyroid’ uptake
  - Decay-corrected % of administered activity in the thyroid
  - May be measured following oral administration of:
    - ^{131}I-iodide
    - ^{123}I-iodide
    - ^{99m}Tc-pertechnetate
- Consists of
  - Wide-aperture, diverging collimator
  - NaI(Tl) crystal (~5 cm thick, ~5 cm diameter)
  - PMT
  - Preamplifier
  - Amplifier
  - Energy discriminator (i.e. energy window)
  - Gantry (stand)

10.4. DETECTION AND COUNTING DEVICES

10.4.5. Organ uptake probe

- Generally supplied as
  - Integrated computerized system
  - With automated
    - Data acquisition
    - Processing capabilities
  - Yield results in terms of % uptake

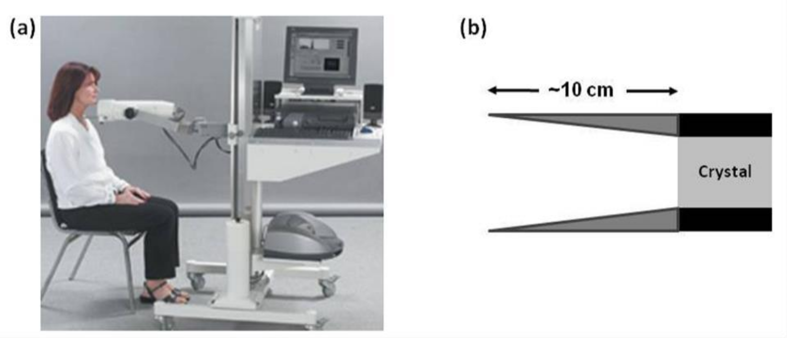
10.4. DETECTION AND COUNTING DEVICES

10.4.5. Organ uptake probe

a) A typical organ (‘thyroid’) uptake probe system

- Integrated computer, set-up
- Large neck to collimator aperture distance (~30 cm)
  - Reduces overall sensitivity
  - BUT serves to minimize the effect of
    - the exact size, shape and position of the thyroid
    - distribution of radioisotope within the gland

b) A diagram (side view) of the open, or ‘flat-field’, diverging collimator



10.4. DETECTION AND COUNTING DEVICES

10.4.5. Organ uptake probe

☐ Determination of thyroid uptake includes:

- Measurement of the thyroid (i.e. neck) count rate
- ‘Thigh’ background count rate
  - Measured over thigh
  - Presumed to approximate the count contribution of extra-thyroidal neck activity
- Ambient (i.e. ‘room’) background
- 1–5 min interval for each measurement

10.4. DETECTION AND COUNTING DEVICES

10.4.5. Organ uptake probe

- Determination of thyroid uptake includes:
  - Standard count rate
    - Often counted in neck phantom
    - Used to automatically correct for:
      - Decay
      - Day-to-day system sensitivity variation
    - Typically a dilution of the administered solution
    - Fraction of administered activity is independently determined < 1

10.4. DETECTION AND COUNTING DEVICES

10.4.5. Organ uptake probe

- Determination of thyroid uptake includes:
  - Thyroid uptake is calculated as follows:

$$\text{uptake}\,(\%) = \frac{C_{\text{neck}}/t_{\text{neck}} - C_{\text{thigh}}/t_{\text{thigh}}}{C_{\text{standard}}/t_{\text{standard}} - C_{\text{room}}/t_{\text{room}}} \times F \times 100\%$$

- C = total counts
- t = measurement time
- F = fraction of administered activity in the standard

  - Known as ‘two-capsule’ method
    - One ^{131}I capsule administered
    - A second, identical one is the standard
      - Counted with each uptake measurement

10.4. DETECTION AND COUNTING DEVICES

10.4.5. Organ uptake probe

Alternatively, ‘One-capsule’ method:

- Patient capsule can be measured immediately before administration
- Each subsequent uptake value can be corrected from time of measurement administration:
  - By multiplying right side of previous equation by $e^{\lambda \Delta t}$

    λ = physical decay constant

    Δt = administration to measurement time

10.4. DETECTION AND COUNTING DEVICES

10.4.5. Organ uptake probe

- For both methods, the fraction of administered activity in the standard is 1

- Some centers administer radio-iodine as a solution
    - More cost effective

- Now often done by ROI analysis of planar gamma-camera images of neck & a standard (i.e. phantom) acquired with parallel-hole collimator

10.4. DETECTION AND COUNTING DEVICES

10.4.5. Organ uptake probe

☐ Organ uptake probes have also been used to measure total body activity

- Example: As part of individualized thyroid cancer dosimetry-based radioiodine treatment
  - Patient may serve as own standard
  - Performed with:
    - Collimator removed from probe
    - Crystal
      - Oriented horizontally
      - Height above the floor = mid-height of patient at ~3 m from crystal
  - Conjugate-view measurements
  - ‘Time 0’ total body count rate S measurement
    - Shortly (30–60 min) after administration
      - Allows some dispersion throughout body
    - Before patient has voided / excreted any activity

10.4. DETECTION AND COUNTING DEVICES

10.4.5. Organ uptake probe

- The % administered activity in the body is:

$$\text{Total body activity }(\%) = \frac{\left[\left(\frac{A}{t_{\mathrm{A}}} - \frac{B}{t_{\mathrm{B}}}\right) \times \left(\frac{P}{t_{\mathrm{P}}} - \frac{B}{t_{\mathrm{B}}}\right)\right]^{1/2}}{\left[\left(\frac{A(0)}{t_{\mathrm{A}(0)}} - \frac{B(0)}{t_{\mathrm{B}(0)}}\right) \times \left(\frac{P(0)}{t_{\mathrm{P}(0)}} - \frac{B(0)}{t_{\mathrm{B}(0)}}\right)\right]^{1/2}} \times 100\%$$

A & P = Anterior / Posterior total counts
B = Room (background) counts
t_A, t_P & t_B = counting intervals A, P & B
(0) = quantities at time 0

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

❑ Quality control (QC)

- Established set of ongoing measurements & analyses
- Designed to ensure procedure / instrument performance is within a predefined acceptable range
- Critical component in routine nuclear medicine practice

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

☐ A sound & compliant QC programme requires

- Documentation
- Organized, retrievable results records
- Written description included in the facility’s procedure manual:
  - Tolerance of results of each procedure
  - Corrective action for an out of tolerance result
  - Signed and dated by facility director, physicist or other responsible individual

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

- Each QC test should have a record of:
  - Initials/signature of individual performing test
  - Test date and time
  - Device make, model and serial number
  - Refernce sources make, model, serial number, activity at date of calibration
  - Result(s)
  - Notation indicating on whether test result was or not acceptable

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

10.5.1. Reference sources

- QC tests often performed with surrogate radionuclides called reference sources
  - Not radionuclides used clinically
    - Longer lived
    - Must match frequency & energy of X and γ-ray emissions of clinical radionuclide
  - Commercially available in various activities & geometries, depending on the application

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

10.5.1. Reference sources

- QC tests often performed with surrogate radionuclides called reference sources
  - In the USA, certified activities must be traceable NIST
    - Helps ensure calibrated activity accuracy
    - A single standard may be used for months to years
    - No need to prepare sources on a daily/weekly basis
    - Avoid possible inaccuracies in dispensing activity
    - Avoids possibility of radioactive contamination

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

10.5.1. Reference sources

- QC tests often performed with surrogate radionuclides called reference sources
  - Must be periodically checked for leakage (i.e. ‘wipe-tested’)
  - Up-to-date inventory must be maintained
  - Still radioactive at end of useful lifespan
    - Must be returned to vendor / third party / otherwise disposed of as radioactive waste

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

10.5.2. Survey meter

- ☐ QC tests of survey meters generally include daily battery check
  - Voltage should be within acceptable range
  - Confirm it’s not contaminated
    - Reproducibly low exposure in the absence of radioactivity
    - Measure background exposure / count rate daily
      - Use area remote from radioactive sources

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

10.5.2. Survey meter

- Check daily for response constancy
  - Measure exposure / count rate of long-lived reference
  - Reproducible measurement geometry
  - Should agree ± 10%; if not, the meter should be re-calibrated
- Checked for accuracy
  - Use long lived reference sources
  - At installation
  - Annually
  - After any repair

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

10.5.2. Survey meter

- Point-source geometry is approximated when
  - Source is ‘small’
    - When compared to photon mean free path
  - Source - meter distance is ‘large’
    - When compared to source dimensions
  - Expected dose rate in air is given by:

$$\dot{D} = \frac{\mathcal{A}_0 e^{-\lambda \Delta t} \Gamma_\delta}{d^2}$$

$\mathcal{A}_0$ = reference source activity at calibration

λ = physical decay constant

Δt = calibration - current measurement time interval

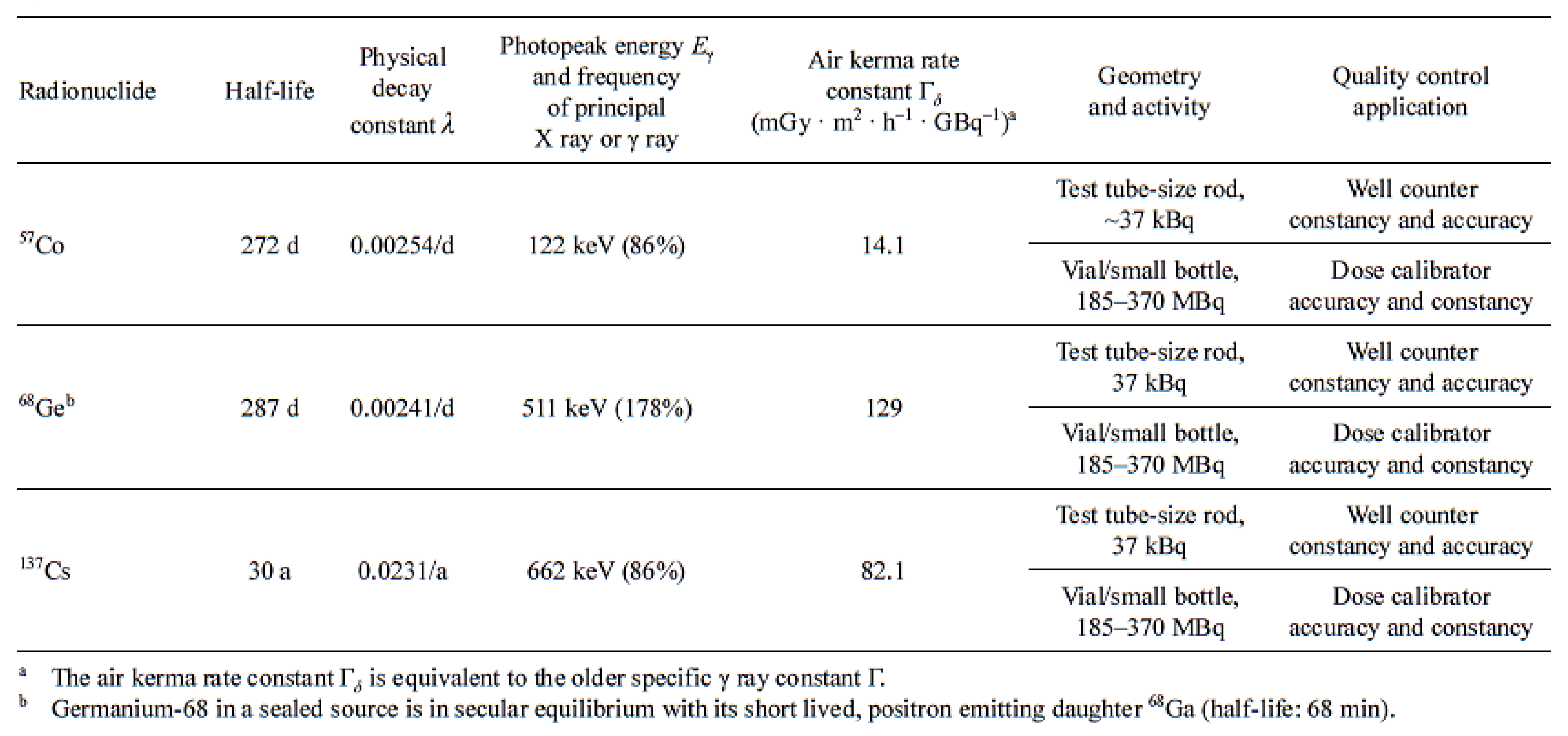
Γ_δ = Air kerma rate constant (γ-energies > 20 keV) of source

d = source-mete distance

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

10.5.2. Survey meter

- Long lived radionuclides used as reference sources for instrumentation quality control



Radionuclide	Half-life	Physical decay constant λ	Photopeak energy E_γ and frequency of principal X ray or γ ray	Air kerma rate constant Γ_δ $(\mathrm{mGy \cdot m^2 \cdot h^{-1} \cdot GBq^{-1}})$[a]	Geometry and activity	Quality control application
^{57}Co	272 d	0.00254/d	122 keV (86%)	14.1	Test tube-size rod, ~37 kBq	Well counter constancy and accuracy
					Vial/small bottle, 185–370 MBq	Dose calibrator accuracy and constancy
^{68}Ge[b]	287 d	0.00241/d	511 keV (178%)	129	Test tube-size rod, 37 kBq	Well counter constancy and accuracy
					Vial/small bottle, 185–370 MBq	Dose calibrator accuracy and constancy
^{137}Cs	30 a	0.0231/a	662 keV (86%)	82.1	Test tube-size rod, 37 kBq	Well counter constancy and accuracy
					Vial/small bottle, 185–370 MBq	Dose calibrator accuracy and constancy

[a] The air kerma rate constant Γ_δ is equivalent to the older specific γ ray constant Γ.

[b] Germanium-68 in a sealed source is in secular equilibrium with its short lived, positron emitting daughter ^{68}Ga (half-life: 68 min).

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

10.5.3. Dose calibrator

- ☐ Routine dose calibrator QC tests
  - Constancy must be checked daily
    - Use NIST-traceable reference source, e.g. ^{57}Co, ^{68}Ge or ^{137}Cs
    - Place in calibrator
    - Record activity reading on each scale
    - Daily readings should agree within 10%

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

10.5.3. Dose calibrator

☐ Routine dose calibrator QC tests

- Accuracy
  - At least quarterly
  - Daily checks recommended
  - At least 2 NIST-sources placed separately in the calibrator
  - Record activity reading on each scale

- Linearity
  - ‘decay method’
  - At least quarterly
  - Daily readings should agree within 10%

10.5.3. Dose calibrator

☐ Measurements at installation

- ^{99m}Tc geometry dependent response
- Volume dependent (2–25 mL) correction factors relative to ‘standard’ volume (e.g. 10 mL)
- Required periodically following installation

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

10.5.3. Dose calibrator

☐ ‘Decay method’ of linearity

- Quarterly
- Use ^{99m}Tc source
  - High activity (~37 GBq)
  - Independently calibrated
- Activity is assayed at 12 h intervals over 3 consecutive days
  - Time = 12 ^{99m}Tc half-lives
  - Activity decays to ~10 MBq
- Plot measured activities versus time on a semi-logarithmic graph
- Draw best fit straight line through data
- Difference between each measured activity point and best fit line should be less than 10%

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

10.5.3. Dose calibrator

☐ ‘Shield method’ to checking linearity

- ^{99m}Tc source
- Place Pb sleeves of increasing ‘decay-equivalent’ thickness in dose calibrator
  - Causes decay-equivalent activity for each sleeve
- Much faster than the decay method
  - Takes minutes instead of days
- Initial decay based calibration of the set of sleeves is recommended

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

10.5.3. Dose calibrator

- ☐ Set of lead-lined plastic sleeves
  - For evaluation of dose calibrator linearity by the shield method
  - The set is supplied with a
    - 0.64 cm thick lead base
    - Color coded unlined sleeve
      - Provide activity measurement equivalent to ‘0’ time point measurement of the decay method
    - 6 color coded lead-lined sleeves
      - Provide attenuation factors
      - Nominally equivalent to decay over 6, 12, 20, 30, 40 and 50 h, respectively

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

10.5.4. Well counter

☐ Routine well counter QC tests

- Photopeak energy window checks
  - If equipped with a multichannel analyser
  - Check energy spectrum is 'peaked'
    - i.e. photopeak should coincide with preset photopeak energy window

- Background
  - Check for each energy window used
  - Count rate should be checked daily
  - Electronic noise & ambient radiation
    - May be relatively high and variable in a nuclear medicine facility
    - Will produce a non-zero/potentially fluctuating count rate
    - Trace contamination will produce inaccurately high count rate values

10.5.4. Well counter

- ☐ Routine well counter QC tests
  - Always include ‘blank’ (i.e. an empty counting tube or vial)
    - To determine the current background count
  - Constancy
    - Use at least one NIST-traceable source
    - Should be counted each day
    - Daily net (i.e. gross minus background) count rates should agree within 10%
  - Efficiency (or sensitivity) (in cpm/kBq)
    - Counter should be calibrated
    - Measure for each radionuclide used
    - Measure at installation, annually & after any repair

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

10.5.5. Intra-operative probe

- ☐ QC tests of intra-operative probes
  - Daily battery and background checks
  - Daily bias check for primary & any backup battery
    - Verify bias/high voltage is within acceptable range
  - Lower counts/count rates from inappropriate energy window may go unnoticed
    - May not provide energy spectrum display
    - May not be possible to visually check peaking

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10.5.5. Intra-operative probe

- QC tests of intra-operative probes
  - Daily checks count rate constancy
    - Use long lived reference source (e.g. ^{57}Co, ^{68}Ge and/or ^{137}Cs)
    - A marked change (e.g. >+10%) in the net count rate from one day to the next may indicate an inappropriate energy window setting or some other technical problem.
  - Reference sources should each be put into some sort of cap
    - To fit reproducibly over the probe
    - To avoid spurious count-rate differences due to source–detector geometry variations

10.5. QUALITY CONTROL OF DETECTION AND COUNTING DEVICES

10.5.6. Organ uptake probe

- Aside from differences in counting geometry and sensitivity, uptake probes and well counters actually have very much in common

- The QC procedures — checks of the photopeak energy window, background, constancy and efficiency — are, therefore, analogous

- Importantly, however, efficiency should be measured more frequently — for each patient — than for a well counter, so that the probe net count rates can be reliably converted to thyroid uptakes for individual patients