Motivation: Radiation Detection Instrumentation

1. You will be responsible for the care of patients and safety of personnel.

2. Need for an objective scientific basis for comparing new technologies. You will be making purchasing decisions.

3. To understand the limits of quantification in radionuclide imaging, especially in regards to therapy or diagnosis.
Detectors encountered in Nuclear Medicine

1. Personnel Dosimeters
2. Dose calibrator and automated dose injection systems
3. Survey meters
4. Well counter
5. Thyroid uptake probe
6. Intra-operative probes
7. Imaging systems
   1. PET/CT
   2. SPECT/CT
Dosimeter – Film Ring and Badge

- **Optically-stimulated (OSL) dosimeter**

- **Pocket dosimeter (ionization chamber)**

- **Thermosluminescent (TLD) dosimeter**
Radiation Detectors: Stored (Absorbed dose) Mode

- Only permits a cumulative estimate of energy deposited within a given time period.
- Usually associated with personnel dosimetry.
- Some personal dosimeters can be read out in real-time.
- Others require separate readout methods.
What type of detector is found in a dose calibrator?
Why use the plastic holder?
Gas-filled Detectors

Ionizing event in air requires about 34 eV

Fig. 4-1. Basic principles of a gas-filled detector. Electrical charge liberated by ionizing radiation is collected by positive and negative electrodes.
Ionization Chambers

Fig. 4-2. Voltage response curve (charge collected versus voltage applied to the electrodes) for a typical ionization chamber. In usual operation, applied voltage exceeds saturation voltage $V_s$ to ensure complete collection of liberated charge.

ATOMLAB 200
Dose Calibrator

- No amplification
- No dead-time
- Signal = liberated charge
- Settings for different isotopes
- Calibrations

From: Physics in Nuclear Medicine (Sorenson and Phelps)
Radiation Detectors: Integrating (Current) Mode

- Integrates collected charge
- Output is proportional to average rate of energy deposition
- Less susceptible to deadtime
- Ideal for high count rate and exposure rate surveying applications
Direct vs. Indirect Interactions

Direct Ionization of gas by charged particle

Beta Particle

Direct vs. Indirect Ionization in a Gas-Filled Detector.
Quality Control: Dose Calibrator

• **Accuracy**
  – use NIST traceable standard; usually Cs-137; must be within ±5% of decay-corrected calibration activity; after installation, after repair and annually
  – ideally test at different energies (e.g., Co-57 or Co-60)

• **Constancy**
  – after accuracy has been determined daily test to monitor consistency of performance (usually use Cs-137)

• **Linearity**
  – test linearity of system, can either use decay method or attenuator sleeve method, done quarterly

• **Geometry**
  – tests response of dose calibrator to different source geometry (e.g., volume in a syringe)
Quality Control: Dose Calibrator

- Linearity

Dose Calibrator Quality Control

Dose Calibrator Linearity

Dose calibrator linearity should be verified at installation, after repair, and on a quarterly basis otherwise.

Right - Photo provided courtesy of Dr. Philip E. Heintz.
Gas-filled detectors
(operates in three ranges)

- Geiger-Muller counters
- Proportional counters
- Ionization chambers
  - Radiation survey meters
  - Dosimeters (dose calibrator)

From: Radiation Detection and Measurement (Knoll, GF)
Geiger-Muller counters

Fig. 4-10. Voltage response curve (pulse amplitude versus applied voltage) for a GM counter.

No energy info
Long dead-time
Thin window probe
Survey Meters

What gives you a more accurate estimate of exposure, the ionization detector or Geiger-Mueller detector?
Radiation Detectors: Counting (Pulse) Mode

- Detects individual photon interactions
- Processes each event in real time
- Typically permit energy to be determined
  - can set energy windows
- Potential count rate limitations (deadtime)

Does a dose calibrator work in counting mode?
Well Counter

High efficiency; however, susceptible to deadtime losses. Try to operate at countrates below 5000 cps. Good for measuring blood samples, urine samples, and wipe tests.
Which previous detector operates almost identically to the thyroid uptake probe?
Inorganic Scintillators

Gamma ray strikes electron (ideally photoelectric interaction)

Primary fast electron dislodges or excites secondary electrons

Excited electrons de-excite and release a scintillation photon
# Inorganic Scintillators

## (physical characteristics)

<table>
<thead>
<tr>
<th>Property</th>
<th>NaI(Tl)</th>
<th>BGO</th>
<th>LSO(Ce)</th>
<th>GSO(Ce)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (gm/cm(^3))</td>
<td>3.67</td>
<td>7.13</td>
<td>7.4</td>
<td>6.71</td>
</tr>
<tr>
<td>Effective Atomic Number</td>
<td>51</td>
<td>75</td>
<td>66</td>
<td>59</td>
</tr>
<tr>
<td>Attenuation Coefficient (@ 511 keV, cm(^{-1}))</td>
<td>0.34</td>
<td>0.955</td>
<td>0.833</td>
<td>0.674</td>
</tr>
<tr>
<td>Light Output (photons/Mev)</td>
<td>40K</td>
<td>~8K</td>
<td>~30K</td>
<td>~20K</td>
</tr>
<tr>
<td>Decay Time</td>
<td>230 ns</td>
<td>300 ns</td>
<td>12 ns</td>
<td>40 ns</td>
</tr>
<tr>
<td>Wavelength</td>
<td>410 nm</td>
<td>480 nm</td>
<td>420 nm</td>
<td>430 nm</td>
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<tr>
<td>Index of Refraction</td>
<td>1.85</td>
<td>2.15</td>
<td>1.82</td>
<td>1.85</td>
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<tr>
<td>Hygroscopy</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Rugged</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>

**relevant detector property**

- sensitivity
- energy & spatial resol.
- counting speed
- photo-sensor matching
- manufacturing / cost
photo-sensor needed with scintillators

Photomultiplier Tube (PMT)

Fig. 4-14. Basic principles of a photomultiplier (PM) tube. (Note: Three dynode stages omitted.)

From: Physics in Nuclear Medicine (Sorenson and Phelps)
Sample Spectroscopy System Hardware

incoming high-energy gamma ray

converted to 1000s of visible photons

~25% converted to electrons

electron multiplication becomes electric signal

(higher gamma energy! (statistical uncertainties!))

larger current or voltage
more electrons
more scintillation photons
higher gamma energy

From: The Essential Physics of Medical Imaging  (Bushberg, et al)
Detector efficiency

A) Intrinsic efficiency – inherent to the detector

B) Geometric efficiency – resulting from geometry of radiation detector and source of radiation

C) Total or overall efficiency
Geometric Efficiency

Source to detector distance

Source to detector geometry

\[ \varepsilon = \frac{\# \text{ photons incident on detector}}{\# \text{ photons emitted from source}} \]
Total Efficiency

\[ \varepsilon_{\text{total}} = \varepsilon_{\text{intrinsic}} \times \varepsilon_{\text{geometric}} \]

You place a 10 \( \mu \text{Ci} \) source of known activity in a well counter. It reports a rate of 37,000 cps. What is the efficiency of the well counter?
Total Efficiency

You place a 10 $\mu$Ci source of known activity in a well counter. It reports a rate of 37,000 cps. You let the source decay to 1 $\mu$Ci and measure it again. This time it measures 4440 cps. What is the efficiency of the well counter?

Why does the efficiency appear to change?

What do you think the countrate would be if you tried to measure a 10 mCi source in the above well counter?
Countrate Performance / Deadtime

Paralyzable and non-paralyzable systems

![Diagram showing True rate, Measured rate, and count rate for paralyzable and non-paralyzable systems]

Rad. Detection Instrumentation, 2015 (RSM)
What type of radiation detector has the highest downtime?

A) Counting detector

B) Integrating (current) mode detector

C) Stored/absorbed dose detector
A NaI(Tl) detector has an energy resolution of 10% at 140 keV. Will its energy resolution be better, worse or the same at 511 keV?
Intra-operative Probes

Examples of surgical or intraoperative probes. Courtesy of IntraMedical Imaging, Los Angeles, CA.

Many make sound like a Geiger-Mueller counter but most either have a scintillator or solid-state detector in the tip.
Quality Control

• **Survey meter**
  – calibrated for accuracy annually and after any repair
  – daily: zero-level, constancy “check source” (±5%), battery

• **Well counter**
  – energy resolution and efficiency: at installation, annually and after repair
  – daily: background, constancy (±5%), pulse height window, chi-square test

• **Thyroid uptake probe**
  – annually: energy resolution and probe efficiency
  – daily: pulse height window, constancy

• **Intra-operative probe**
  – annually: energy resolution and probe efficiency
  – prior to each use: constancy and pulse height window, manufacturer recommendations
Other Types of Detectors
Semiconductor Detectors

• Works on same principle as gas-filled detectors (i.e., production of electron-hole pairs in semiconductor material)
• Only ~3 eV required for ionization (~34 eV, air)
• Usually needs to be cooled (thermal noise)
• Usually requires very high purity materials or introduction of “compensating” impurities that donate electrons to fill electron traps caused by other impurities
Semiconductor Detectors

- CdZnTe detectors - can operate at room temperature
Organic Liquid Scintillators
(liquid scintillator cocktail)

- Organic solvent - must dissolve scintillator material and radioactive sample
- Primary scintillator (p-terphenyl and PPO)
- Secondary solute (wave-shifter)
- Additives (e.g., solubilizers)
- Effective for measuring beta particles (e.g., H-3, C-14).
Imaging Systems: PET/CT and SPECT/CT
What piece of equipment would you use to measure the activity of a pure beta emitter?
What piece of equipment would you use to measure the activity of a pure beta emitter?
What piece of equipment would you **not** use to determine if there is contamination from a wipe test?

From: The Essential Physics of Medical Imaging (Bushberg, et al)
What piece of equipment would you not use to determine if there is contamination from a wipe test?
64 year old female with chest pain arrives for nuclear stress test
Tc-99m Sestamibi Myocardial Perfusion Stress Study

What is wrong with this picture?
30 year old male arrives for whole-body FDG oncologic workup
F18-FDG PET /CT Study

What is wrong with this picture?

From: The Essential Physics of Medical Imaging  (Bushberg, et al)
You find a test tube with some fluid in it and a radiation sticker on it left on a counter. What would you do to find out what it contained?

Simplest way to determine whether it is radioactive?

How to determine how much radioactivity?

How to determine what radionuclide?
Question

Of the following, the most efficient detector for X-rays is:

A. Geiger counter
B. NaI(Tl) detector
C. Single channel analyzer
D. Ionization chamber
E. Pocket (self-reading) dosimeter
Question

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Gas multiplication occurs in:

A. Geiger-Mueller counter
B. NaI(Tl) detector
C. Semiconductor detector
D. Ionization chamber
E. Dose calibrators
Question

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Question (true or false)

A 1 MeV beta particle produces a pulse of the same amplitude in a Geiger-Mueller detector as a 200 keV beta particle?
Question (true or false)

A 1 MeV beta particle produces a pulse of the same amplitude in a Geiger-Mueller detector as a 200 keV beta particle?

TRUE
Question

For a pulse mode detector, overall system efficiency is independent of?

A. activity level
B. intrinsic efficiency
C. counting interval
D. pulse height analyzer window alignment
Question

For a pulse mode detector, overall system efficiency is independent of?

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B. intrinsic efficiency
C. counting interval
D. pulse height analyzer window alignment
Question

The GM survey detector?

A. is useful for accurate estimates of exposure in air
B. can be used for surveying in high radiation fields without significant deadtime
C. is useful for low-level radiation surveying because of its relatively high efficiency
D. has a response that fluctuates with small variations in operating voltage
Question

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Question

A counting system employing a 20% energy window centered on the photopeak of Tc99m would have a lower and upper energy threshold set at ? and ?

A. 100 keV, 140 keV
B. 140 keV, 180 keV
C. 80 keV, 180 keV
D. 126 keV, 154 keV
E. 112 keV, 168 keV
Question

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