Bioengineering 508: 
Physical Aspects of Medical Imaging 
http://courses.washington.edu/bioen508/

For questions, remarks, discussions, errors in the book: 
Class Discussion Board (link from class website) 
Monitored by instructors frequently

Organizer: Paul Kinahan, PhD 
Adam Alessio, PhD 
Ruth Schmitz, PhD 
Lawrence MacDonald, PhD 

Imaging Research Laboratory 
http://depts.washington.edu/nucmed/IRL/ 
Department of Radiology 
University of Washington

Homework 
for Oct. 25

1. Read Suetens sections 8.5 – 8.10

2. Find 2 medical images of abnormal physiology using SPECT or PET

Place these images in a document
• Write 1–2 brief sentences describing each image
• Write 1–2 brief sentences describing differences between the images.
• Write 1–2 brief sentences describing what the image values represent physically.
Announcements

1. Today’s homework can be handed in tomorrow for those having trouble finding planar gamma camera images.
2. Signup sheet indicating names of groups for class project
   (Prof. Kinahan will assign undesignated students tomorrow)
3. Field trip to UW Radiology Dept. will be Sat. 10/28
   late morning or early afternoon preference?
4. NO CLASS on Nov. 1!
   The exam will be administered over the web – take-home exam.

Radiation Physics
Nuclear Medicine
Detectors and Systems

18 Oct. 2006
Larry MacDonald
macdon@u.washington.edu
Overview of today’s lecture

- **Emission vs. Transmission Imaging**
- Nature of nuclear radiation
  - Isotopes used in nuclear medicine
- Detection methods
- Counting statistics
- Imaging systems
  - Planar gamma scintigraphy

Tomographic systems (SPECT & PET) covered in a later lecture

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**Emission vs. Transmission imaging**

Transmission imaging; X-ray methods (radiograph, CT, mammography, angiography)

Radiation position & strength (number, energy*) is known

\[ N = N_0 e^{\mu x} \quad \rightarrow \quad N_0 \text{ known, measure } N, \text{ infer } \mu \]

*What ambiguity exists?*
**Emission imaging**

Radiation position & strength *unknown*
Energy *is* known (mono-energetic)

Scintillation Camera

Energy resolution important to reject scattered gammas

~99.95% gamma rays blocked - NOT very sensitive
Emission vs. Transmission imaging

Transmission imaging (x-ray methods)
Measures attenuation coefficient:
\[ \mu \sim \text{density of tissue} \rightarrow \text{ANATOMY} \]

Emission imaging (gamma-ray methods; planar, SPECT, PET)
Measures concentration of injected radio-pharmaceutical \( \rightarrow \) corresponds to \text{WHAT}?

100s of radio-pharmaceuticals designed to highlight a variety of \text{PHYSIOLOGICAL} processes.
Referred to as
“\textit{functional imaging}”
“\textit{molecular imaging}”

Overview of today’s lecture

• Emission vs. Transmission Imaging

• \textit{Nature of nuclear radiation}
  - Isotopes used in nuclear medicine

• Detection methods

• Counting statistics

• Imaging systems
  - Planar gamma scintigraphy
Nuclear radiation results from unstable nuclei

Nuclear stability is a balance between electromagnetic repulsion of protons and strong force interaction among all nucleons (protons and neutrons).

There are ~ 2,450 isotopes of the ~ 100 elements in the Periodic Table, ~300 of which are naturally occurring, the others are human-made.

Several mechanisms for unstable nuclei to decay to stable isotopes: fission, $\alpha$-, $\beta$-, $\gamma$-emission, e$^-$ capture.

Frequently there are multiple decay steps to reach stability.

Each decay step is described by an exponential process with a characteristic decay time $\tau$ — Half-life of the isotope $T_{1/2} = \tau / \ln(2)$

$$N=N_0e^{-t/\tau}$$

Types of radiation relevant to Nuclear Medicine

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
<th>Mass (MeV/c$^2$)</th>
<th>Charge (e$^-$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>e-, $\beta$-</td>
<td>0.511</td>
<td>-1</td>
</tr>
<tr>
<td>Positron</td>
<td>e+, $\beta$+</td>
<td>0.511</td>
<td>+1</td>
</tr>
<tr>
<td>Alpha</td>
<td>$\alpha$</td>
<td>3700</td>
<td>+2</td>
</tr>
<tr>
<td><strong>Photon</strong></td>
<td>$\gamma$</td>
<td>no rest mass</td>
<td>none</td>
</tr>
</tbody>
</table>

Electron mass $= 9.11 \times 10^{-31}$ kg
Electron charge $= 1.6 \times 10^{-19}$ Coulombs
Joules-to-electronVolts: $1.6 \times 10^{-19}$ J/eV
$E = mc^2$
α Particle Range in Matter
2 protons + 2 neutrons (helium nucleus)
mono-energetic
NOT USED FOR IMAGING

- Loses energy in a more or less continuous slowing down process as it travels through matter.
- The distance it travels (range) depend only upon its initial energy and its average energy loss rate in the medium.
- The range for an α particle emitted in tissue is on the order of μm’s.

β Decay
continuous energy spectrum
Autoradiography (in-vitro imaging)
Proximity imaging (? research probes)

- β particle ranges vary from one electron to the next, even for βs of the same energy in the same material.
- This is due to different types of scattering events the β encounters (i.e., scattering events, bremsstrahlung-producing collisions, etc.).
- The β range is often given as the maximum distance the most energetic β can travel in the medium.
- The range for β particles emitted in tissue is on the order of mm’s.
Interactions of Photons with Matter

Exponential Penetration: \[ N = N_0 e^{-\mu x} \]

\( \mu_{PE}, \mu_{CS}, \text{etc.}, \) dependent on \( E, Z, \) density.

\[ \lambda \sim c \text{ m's} \]

\( \mu \) depends on \( E, Z, \) density.

**Photoelectric effect** \((\mu_{PE})\)
- all photon energy transferred to an \( e^- \) photon is absorbed; ceases to exist

**Compton scattering** \((\mu_{CS})\)
- photon ‘bounces’ off an \( e^- \)
- part of the photon energy transferred to the \( e^- \)
- lower energy photon redirected between \( 0\degree – 180\degree \)

Pair production
- positron-electron pair is created
- requires photons above 1.022 MeV

Coherent (Rayleigh) scattering
- photon deflected with very little energy loss
- only significant at low photon energies (<50 keV)

Nuclear Medicine Radionuclide Requirements

**Emission imaging**
- Charged, massive particles (\( \alpha-, \beta- \)rays) cannot penetrate tissue for emission imaging.
- \( \rightarrow \) need Gamma-Ray emitters [exception: \( \beta^+ \) emitters for PET]

**Half-life**
- "Too long" leaves damaging radiation in patient after imaging is complete, delivering unnecessary dose.
- "Too short" does not permit production, preparation, delivery, administration, and internal distribution for practical imaging tasks.
- \( \rightarrow \) Typically many minutes – hours – a few days is considered about right.

**Energy of Gamma-Ray**
- If the energy is "too low" a majority of the photons will be attenuated and not reach the camera (cf. \( \alpha-, \beta- \)rays).
- If the energy is "too high" then the \( \gamma \)-rays will pass through the camera without being absorbed by the detector and it is difficult to colimate.
- \( \rightarrow \) Energies of ~100–500 keV are used.

**Complexity**
- A decay scheme with "too many" emissions confounds the imaging process.
- \( \rightarrow \) Select isotopes with relatively simple decays schemes; ideally one or two \( \gamma \)-rays, no \( \beta^- \) or \( \alpha \)-rays.

**Chemical properties**
- Isotope must be incorporated into a pharmaceutical or other organic compound.
- \( \rightarrow \) Isotopes amenable to chemical, pharmaceutical, and sterile processing.
### List of Nuclear Medicine Radionuclides for “single photon” imaging (i.e. excluding PET)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Gamma energy (keV)</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tc-99m</td>
<td>140.5</td>
<td>6.03 hours</td>
</tr>
<tr>
<td>I-131</td>
<td>364, 637</td>
<td>8.06 days</td>
</tr>
<tr>
<td>I-123</td>
<td>159</td>
<td>13.0 hours</td>
</tr>
<tr>
<td>I-125</td>
<td>35</td>
<td>60.2 days</td>
</tr>
<tr>
<td>In-111</td>
<td>172, 247</td>
<td>2.81 days</td>
</tr>
<tr>
<td>TI-201</td>
<td>~70, 167</td>
<td>3.044 days</td>
</tr>
<tr>
<td>Ga-67</td>
<td>93, 185, 300</td>
<td>3.25 days</td>
</tr>
</tbody>
</table>

http://en.wikipedia.org/wiki/Radiopharmaceutical

### Technetium-99m

**Tc** is a gamma emitter: 140 keV

<table>
<thead>
<tr>
<th>Name</th>
<th>Investigation</th>
<th>Route of administration</th>
<th>In-vivo / In-vivo</th>
<th>Imaging / non-imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tc-99m pertechnetate</td>
<td>Therapeutic and thyroid imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m pertechnetate</td>
<td>Brain imaging</td>
<td>Iv</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Human album</td>
<td>First pass peripheral vascular imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Human album</td>
<td>Brain imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Human album macroaggregates or microspheres</td>
<td>Lung perfusion imaging with venography</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Phosphonates and phosphates</td>
<td>Bone imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m DTPA (diethylenetriaminepenta-acetic acid)</td>
<td>Renal imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m DTPA (diethylenetriaminepenta-acetic acid)</td>
<td>First pass blood flow studies</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m CMAA (dimercapto-succinic acid)</td>
<td>Lung ventilation imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m CMAA (dimercapto-succinic acid)</td>
<td>Renal imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Colloid</td>
<td>Bone marrow imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Colloid</td>
<td>Gi bleeding</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Colloid</td>
<td>Myocardial imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Colloid</td>
<td>Peripheral vascular imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Colloid</td>
<td>Oesophageal transit and reflux imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Colloid</td>
<td>Eye drop</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Colloid</td>
<td>Bone marrow system imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Colloid</td>
<td>Red cell volume</td>
<td>IV</td>
<td>In-vivo</td>
<td>Non-imaging</td>
</tr>
<tr>
<td>Tc-99m Red blood cells</td>
<td>Gi bleeding</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m MAG3 (mercaptoacetylglycine)</td>
<td>Cardiac blood pool imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m MAG3 (mercaptoacetylglycine)</td>
<td>Renal imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m MAG3 (mercaptoacetylglycine)</td>
<td>First pass blood flow imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m MAG3 (mercaptoacetylglycine)</td>
<td>Central blood flow imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m MAG3 (mercaptoacetylglycine)</td>
<td>Renal imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m MAG3 (mercaptoacetylglycine)</td>
<td>Respiratory system imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m MAG3 (mercaptoacetylglycine)</td>
<td>Bone marrow system imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m MAG3 (mercaptoacetylglycine)</td>
<td>Non-specific tumour imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m MAG3 (mercaptoacetylglycine)</td>
<td>Bone marrow system imaging</td>
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<tr>
<td>Tc-99m MAG3 (mercaptoacetylglycine)</td>
<td>Myocardial imaging</td>
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<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Sestamibi</td>
<td>Cardiac blood pool imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Sestamibi</td>
<td>Renal imaging</td>
<td>IV</td>
<td>In-vivo</td>
<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Sestamibi</td>
<td>First pass blood flow imaging</td>
<td>IV</td>
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<td>Imaging</td>
</tr>
<tr>
<td>Tc-99m Sestamibi</td>
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</tbody>
</table>

http://en.wikipedia.org/wiki/Radiopharmaceutical
Single photon isotope production

Nuclear Reactor
Neutron bombardment of target isotopes leads to fission with useful radio-isotope fragments.

Generator
Long-lived parent isotope decays to short-lived daughter radio-isotope for use in the clinic (parent produced in, e.g., a nuclear reactor).
Daughter separated from parent chemically in the ‘generator’.

Cyclotron
Accelerates charged particles (e-, p, α, ²H) that collide with targets resulting in radio-isotopes. Used to generate PET radio-isotopes.

Overview of today’s lecture
- Emission vs. Transmission Imaging
- Nature of nuclear radiation
  - Isotopes used in nuclear medicine
- **Detection methods**
- Counting statistics
- Imaging systems
  - Planar gamma scintigraphy
Basic Radiation Detector System

What do you want to know about the radiation?
- Energy?
- Position (where did it come from)?
- How many / how much?

Important properties of radiation detectors
- Energy resolution
- Spatial resolution
- Sensitivity
- Counting Speed
Pulse Mode versus Current Mode

• Pulse mode
  – Detect individual photons
  – Required for NM imaging applications
• Current mode
  – Measures average rates of photon flux
  – Avoids dead-time losses
  – Typically used in x-ray systems (CT)

Types of Radiation Detectors

detection modes / functionality

• Counters
  – Number of interactions
  – Pulse mode
• Spectrometers
  – Number and energy of interactions
  – Pulse mode
• Dosimeters
  – Net amount of energy deposited
  – Current mode
• Imaging Systems
  – CT = current mode
  – NM = pulse mode
Types of Radiation Detectors

physical composition

- Gas-filled detectors
- Solid-state (semiconductor) detectors
- Organic scintillators (liquid & plastic)
- Inorganic scintillators

scintillators operate with a **photo-sensor**
(i.e. another detector)

Radiation detectors used in Nuclear Medicine
Gas-filled Detectors
Can be used for imaging, but low sensitivity (low density)

Fig. 4.1. Basic principles of a gas-filled detector. Electrical charge liberated by ionizing radiation is collected by positive and negative electrodes.

Gas-filled detectors
(operates in three ranges)

Geiger-Muller counters

Proportional counters

Ionization chambers
- Radiation survey meters
- Dosimeters (dose calibrator)
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

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

From: Physics in Nuclear Medicine (Sorensen and Phelps)
**Organic Liquid Scintillators**
*(NOT USED FOR IMAGING)*

- 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).

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**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**

- High purity germanium – need liquid nitrogen (77K)
- $\text{ Cd}_{(1-x)}\text{Zn}_x\text{Te}$ detectors – can operate at room temperature

**Inorganic Scintillators**

*(physical characteristics)*

Absorption of radiation lifts electrons from valence to conduction band

Impurities (activators) create energy levels within the band gap permitting visible light scintillations
Inorganic Scintillators
(physical characteristics)

<table>
<thead>
<tr>
<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>
</tr>
<tr>
<td>Effective Atomic Number</td>
<td>51</td>
<td>75</td>
<td>66</td>
</tr>
<tr>
<td>Attenuation Coefficient (@ 511 keV, cm$^{-1}$)</td>
<td>0.34</td>
<td>0.955</td>
<td>0.833</td>
</tr>
<tr>
<td>Light Output (photons/Mev)</td>
<td>40K</td>
<td>~8K</td>
<td>~30K</td>
</tr>
<tr>
<td>Decay Time</td>
<td>230 ns</td>
<td>300 ns</td>
<td>12 ns</td>
</tr>
<tr>
<td>Wavelength</td>
<td>410 nm</td>
<td>480 nm</td>
<td>420 nm</td>
</tr>
<tr>
<td>Index of Refraction</td>
<td>1.85</td>
<td>2.15</td>
<td>1.82</td>
</tr>
<tr>
<td>Hygroscopy</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Rugged use</td>
<td>SPECT</td>
<td>PET</td>
<td>PET</td>
</tr>
</tbody>
</table>

relevant detector property

sensitivity

energy & spatial resol.
counting speed

photo-sensor matching manufacturing / cost

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**photo-sensor needed with scintillators**

**Photomultiplier Tube (PMT)**

![Photomultiplier Tube (PMT)](image)

Fig. 4.14. Basic principles of a photomultiplier (PMT) tube. (Note: Three dynode stages omitted.)