5: Emission (Computed) Tomography

1. What is a tracer?
2. Why is collimation necessary and what are its consequences?
3. How are the effects of attenuation taken into account?
4. What is the principle of x-ray detection?
   scintillation
5. How are scintillation photons converted to an electrical signal?
6. How can scattered photons be eliminated?

After this course you
1. Understand the reason for collimation in imaging γ-emitting tracers and its implication on resolution/sensitivity
2. Understand the implications of x-ray absorption on emission tomography
3. Understand the basic principle of radiation measurement using scintillation
4. Are familiar with the principle/limitations of photomultiplier tube amplification
5. Understand the use of energy discrimination for scatter correction

What is Emission Computed Tomography?

Until now: CT and x-ray imaging measure attenuation of incident x-ray

Emission tomography: X-rays emitted by exogenous substance (tracer) in body are measured

Two issues:
1. How to determine directionality of x-rays?
2. Absorption is undesirable

What is a tracer?
Exogenously administered substance (infused into blood vessel) that
(a) alters image contrast (CT, MRI)
(b) has a unique signal (γ emitting)

→ Emission computed tomography

Typical tracers for emission tomography

<table>
<thead>
<tr>
<th>Half-life (h)</th>
<th>Photon Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>99mTc</td>
<td>6</td>
</tr>
<tr>
<td>201Tl</td>
<td>73</td>
</tr>
<tr>
<td>123I</td>
<td>13</td>
</tr>
<tr>
<td>133Xe</td>
<td>0.08</td>
</tr>
</tbody>
</table>
What are the basic elements needed for $\gamma$-emitter imaging?

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5-5

**5-2. How can directionality of x-rays be established?**

**Collimation**

**Problem:** Photon detection alone does not give directionality.

**Solution:**

- Collimation establishes direction of x-ray
- Consider one detector, assuming perfect collimation (and neglecting attenuation, see later)
- $S(y) = \int_{-\infty}^{\infty} C_T(x,y) \, dx$
  - $C_T(x,y)$: tissue radioactivity
  - Line of incidence (LOI)
  - Radon transform
  - Reconstruction as in CT

**Impact of collimation on resolution**

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5-6
5-3. How to deal with attenuation of the emitted x-rays?

Result of x-ray absorption in tissue

Signal measured from a homogeneous sphere ($C_T(x,y) = \text{constant}$)

Intensity distortion: Cause?

$T = \frac{n(D)}{N_0} = e^{-\mu D}$

1. Depends on object dimension and source location ($D = f(\text{object})$)

Consider point source:
Attenuation depends on location of source in tissue

2. Photon energy $\mu = f(E)$

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Collimator resolution:

Two objects have to be separated by distance $> R$

$R = \frac{d(a + b)}{a_e}$

$a_e = a - \frac{6d}{\mu} \left( \frac{1}{a} - \frac{3}{\mu} \right)$

(Why?)

Septa penetration < 5% occurs when $t_{Septa}:
\text{t}_{Septa} = \frac{6d}{\mu} \frac{a}{a - 3/\mu}$

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How does collimation affect resolution?

It’s never perfect …

Perfect collimation, i.e. resolution?

$\frac{d}{a} \rightarrow 0$

$\mu_{collimator} \rightarrow \infty$

Impossible to achieve (Why?)

Imaging Acquisition System

Collimator resolution:

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What are the basic steps in attenuation correction?

**Attenuation correction procedure**

A. Estimated object geometry and estimated $\mu(x,y)$ or measured $\mu(x,y)$
B. Transmission loss: $T(\text{projection}) = f(\mu(\text{object}), \text{projection})$
C. Attenuation correction $A(x,y) = 1/T(x,y)$
D. Corrected image $C_{\text{corr}}(x,y) = A(x,y) C(x,y)$

**Problem** is prior knowledge needed for A (i.e. $\mu(x,y)$)

**Attenuation correction rarely applied!**

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How to simplify attenuation correction?

by measuring at 180° using geometric mean

**Problem**: Spatial dependence of correction

$D = x_1 + x_2$

Consider point source:

$S_1(y) = C_T(x_1, y) e^{-\mu_1}$
$S_2(y) = C_T(x_2, y) e^{-\mu_2}$

**Solution**: Geometric mean of the two 180° opposite signals:

$\sqrt{S_1 \cdot S_2} = C_T(x, y) e^{-\mu D/2}$

$D = x_1 + x_2$

Measure at 180° simultaneously and take the geometric mean

→ attenuation correction depends only on dimension of object along the measured Radon transform

NB. This correction can be used in emission tomography for focal uptake (i.e. uptake limited to a specific region)
5-4. What is the principle of x-ray detection?
Collimation, followed by scintillation and amplification

Scintillator crystal
e.g. Ti-doped SodiumIodide (NaI)

Photomultiplier
Tube

γ-energy \( \propto \) # scintillation photons \( \propto \) Signal

What is Scintillation?

Sequence of events in scintillation crystal
1. Atom ionized by Compton interaction \( \rightarrow \) Electron-hole pair
2. Hole ionizes activator, electron falls into activator
3. Activator is deactivated by emission of Photons (10^{-7} sec)

Efficiency of scintillators

\[\eta = \frac{\text{energy of scintillation light}}{\text{energy deposited}} \propto \frac{Tq_{a}}{W_{e-h}}\]

\(T\) = energy transfer efficiency from excited ion to luminescence centre
\(q_{a}\) = quantum efficiency of luminescence centre
\(W_{e-h}\) = energy required to create one electron-hole pair
What elements characterize scintillation materials?

Overview of some crystals

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Density (g/cm³)</th>
<th>Attenuation Coefficient (cm⁻¹ @ 511 keV)</th>
<th>Light yield ph/keV</th>
<th>λ (nm)</th>
<th>τ (ns)</th>
<th>Zeff</th>
<th>Refr. Index</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdWO₄</td>
<td>7.90</td>
<td>0.886</td>
<td>15</td>
<td>495</td>
<td>~10⁶</td>
<td>73</td>
<td>2.15</td>
<td>13%</td>
</tr>
<tr>
<td>Bi₄Ge₃O₁₂</td>
<td>7.13</td>
<td>0.964</td>
<td>7</td>
<td>480</td>
<td>300</td>
<td>51</td>
<td>1.85</td>
<td>100%</td>
</tr>
<tr>
<td>(Y,Gd)₂O₃:Eu,Pr</td>
<td>5.9</td>
<td>0.503 - 0.637</td>
<td>15</td>
<td>610</td>
<td>~10⁶</td>
<td>59</td>
<td>2.79</td>
<td>100%</td>
</tr>
<tr>
<td>Ga₂O₃:Pr,Ce,F</td>
<td>7.34</td>
<td>0.786</td>
<td>10</td>
<td>510</td>
<td>~10³</td>
<td>59</td>
<td>1.85</td>
<td>100%</td>
</tr>
<tr>
<td>NaI:Tl</td>
<td>3.67</td>
<td>0.343</td>
<td>11</td>
<td>415</td>
<td>230</td>
<td>66</td>
<td>1.59</td>
<td>79%</td>
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<tr>
<td>Gd₂SiO₅:Ce</td>
<td>6.71</td>
<td>0.704</td>
<td>11</td>
<td>430</td>
<td>300</td>
<td>66</td>
<td>1.56</td>
<td>79%</td>
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<tr>
<td>Lu₂SiO₅:Ce</td>
<td>7.4</td>
<td>0.869</td>
<td>10</td>
<td>420</td>
<td>40</td>
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<td>1.59</td>
<td>79%</td>
</tr>
<tr>
<td>LuAlO₃:Ce</td>
<td>8.34</td>
<td>0.956</td>
<td>9</td>
<td>365</td>
<td>17</td>
<td>59</td>
<td>1.85</td>
<td>100%</td>
</tr>
<tr>
<td>LuPO₄:Ce</td>
<td>6.53</td>
<td>0.735</td>
<td>17</td>
<td>360</td>
<td>25</td>
<td>59</td>
<td>1.85</td>
<td>100%</td>
</tr>
</tbody>
</table>

Requirements for scintillator

- High yield
- Good linearity
- Small time constant τ
- Transparent for scintillation light λ
- Good mechanical properties
- Refraction index close to 1.5

Most of the energy of the x-ray is lost as heat (to lattice), see

\[ E_{400\text{nm}}[\text{keV}] = \frac{hc}{\lambda} = \frac{1.2}{\lambda} \text{[nm]} \]

\[ E_{400\text{nm}}[\text{keV}] = \frac{1.2}{400 \text{ keV}} = 3 \text{eV} \]

<20keV or <120eV/keV ph/keV

5.5. How is the scintillation light converted to an electrical signal?

Photomultiplier tube (PMT) - Noiseless amplification

Photocathode

Dyode

Anode

Pulse Height Analyzer

How to increase resolution beyond PMT dimensions?
5-6. How to discriminate scattered photons?

**Tc-99m spherical phantom (w. holes)**

Most scattering is by Compton

$$E_f = \frac{E_i}{1 + E_i \left(1 - \cos \theta \right)}$$

Measure $E_f$ → identify severely scattered photons

<table>
<thead>
<tr>
<th>theta/Ei</th>
<th>100</th>
<th>140</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>99</td>
<td>138</td>
</tr>
<tr>
<td>45</td>
<td>95</td>
<td>130</td>
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<tr>
<td>90</td>
<td>84</td>
<td>110</td>
</tr>
<tr>
<td>110</td>
<td>79</td>
<td>102</td>
</tr>
<tr>
<td>180</td>
<td>72</td>
<td>90</td>
</tr>
</tbody>
</table>

**Counts**

**Primary scatter**

**Total**
What processes contribute to the Scintillation light spectrum?

Scintillation signal depends on x-ray energy.

Nal (Ti) scintillation peak for Cs-37: 662 keV

- max. energy of the recoil electron (i.e. 662 keV photon scattered by 180°)
- energy of 662 keV photon scattered by 180°
- light from Compton events
- secondary photons escaped from crystal

SPECT summary

Single Photon Emission Computed Tomography

1. Measurement of single photon emitters injected into subject
2. Collimation ensures x-ray directionality (⇒ backprojection)
3. Absorption is undesirable
4. Photon energies comparable to CT ⇒ SPECT-CT