1. Short overview about ionizing radiation and its interaction with matter
2. Revision about the main radiation detectors
3. Scintillation based detectors
4. Diagnostic images
5. Gamma Cameras
6. Quality Control
7. Radiation protection
Ionizing radiation

Ionizing radiations are those which interact with matter through processes which generates ionization

Ionizing radiation types

Indirectly ionizing:

Particles: Neutrons
Electromagnetic: Gamma, X rays

Directly ionizing:

Charged particles: Alpha, Beta (+ or -), Protons
How these radiations interact with matter?

**Charged particles:**
- Ionization
- Excitation

**Electromagnetic:**
- Rayleigh Effect
- Photoelectric Effect
- Compton Effect
- Pair production
- Photonuclear Effect
Photo electric effect  1.swf
Compton Effect

- Incoming Photon, $E_1, \lambda_1$
- Scattered Photon $E_2 < E_1, \lambda_2 > \lambda_1$
- Scattered Electron $E_e = E_1 - E_2 - E_{\text{Binding}}$

$E_2 < E_1, \lambda_2 > \lambda_1$
Energy Distribution of Electrons
from Compton Scattering
Pair production

Incoming Photon $E_\gamma$

Electron $T^-$
Positron $T^+$
What happens after the interaction?

- Characteristic X rays
- Bremsstrahlungen
- Heat
Which are the effects or ionizing radiation in matter?

Which parameters are important to be considered?

- Density
- Conductivity

Which would be the best material to detect ionizing radiation?

- A solid?
- A liquid?
- A gas?
Gas based detectors

Ionization chambers
  - Pulse mode
  - Charge mode
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Proportional counters

\[ \varepsilon = \frac{V}{r \ln(b/a)} \]
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Geiger-Müller Counters
Semiconductors, metals, insulators
What happens when the electronic shells become closer?
Atom Excited by Radiation

Energy

Conduction Band

Forbidden Gap

Valence Band

Atom is excited by interaction with radiation, moving an electron from the valence band to the conduction band.

Atom De-excites Emitting Light Photon

Energy

Conduction Band

Forbidden Gap

Valence Band

Energy of emitted photon equals the energy of the gap and wavelength is too short.
Inorganic Scintillators 2.swf 3.swf

FIG. 6.2 Allowed and forbidden energy bands of a crystal.
Adding Impurity/Activator

Adding impurity to crystal adds extra energy levels in the forbidden gap.

Atom De-excites Emitting Light Photon

Atom de-excites in two-step process, emitting lower energy, longer wavelength photons.
Organic Scintillators
Photomultiplier tubes
Photomultiplier tube
Photomultiplier tube
BLOCK DIAGRAM OF A RADIATION DETECTOR BASED ON A SCINTILLATOR (Pulse Mode)
Diagnostic Imaging

- Radiology – x-ray machines, CT
- Nuclear Medicine Gamma cameras, PET
- Magnetic resonance
X-ray tube

- Focusing cap
- Tungsten target
- Filament
- Copper supports
- X rays
Radiology
Effect of the scattered radiation
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Grids

- OBJECT
- Grid
- Absorber strips
- Radiographic film
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CT – technique
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CT Computerized Tomography

- X ray tube
- Collimators
- Detector
CT is based on the calculation of the absorption of radiation in a determined value of a material. This calculation is performed with information obtained in different position through the movement of the set x-ray tube – detectors. Considering the following figure, each square represents a cube which is named "voxel". The attenuation of each beam will be derived from the sum of the individual contribution of each voxel.

\[
\begin{array}{cccc}
A_{11} & A_{12} & A_{13} & A_{14} \\
A_{21} & A_{22} & A_{23} & A_{24} \\
A_{31} & A_{32} & A_{33} & A_{34} \\
A_{41} & A_{42} & A_{43} & A_{44} \\
\end{array}
\]
The attenuation of a radiation beam after crossing a determine layer of a material is given by:

\[ I = I_0 e^{-\mu x} \]

Where \( \mu \) is the linear attenuation coefficient for the energy of the incident radiation and \( x \) the material thickness.

For the beam \( F_1 \) the total attenuation will be given by the sum of the attenuation in \( A_{12}, A_{21}, A_{31}, A_{41} \). Therefore, \( I(F_1) \) will be equal to \( I_0(F_1) \) multiplied by the individual attenuations;

\[ I = I_0 e^{-\mu(A_{11})x} e^{-\mu(A_{21})x} e^{-\mu(A_{31})x} e^{-\mu(A_{41})x} \]

Applying the Neperian logarithm to both sides of this equation we have:

\[ \ln(I) = \ln(I_0 e^{-\mu(A_{11})x} e^{-\mu(A_{21})x} e^{-\mu(A_{31})x} e^{-\mu(A_{41})x}) = \ln(I_0) - \mu(A_{11})x - \mu(A_{21})x - \mu(A_{31})x - \mu(A_{41})x \]

The same is valid for the beam \( F_2 \). Using a set of beams, we get a set of equations which variables are the attenuation coefficients for the ¨voxels¨. This set of equations can be solved applying numeric methods. Having the linear attenuation coefficients for each voxel available it is possible to generate an image of this set of ¨voxels¨ providing a gray scale greater or smaller depending on the calculated attenuation coefficient.
Computed tomography

CT gives anatomical information
CT: skeleton - neuro
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Magnetic Resonance Imaging

MRI gives anatomical information
Nuclear Medicine

1) A labeled material (carrying a radioactive material) is injected in the patient
2) The tumor cells or the tissue of interest will concentrate more or less the labeled material
3) A “picture” of the radioactive material is obtained utilizing a special detector
What is needed?

1) A radioactive material that can be used as a label and which has the appropriated energy range of photons and with a short live time

2) A large detector (Scintillator)

3) A system for measuring the light produced by the radiation (PMT tubes)

4) A system for determining the position of the interaction of the radiation with the detector (Weighting and calculation systems)

5) The scattered radiation is not contributing for the image, it should be avoided and discriminated (Collimator and MCA)

6) A system for computing and processing the data (Image processor)

7) A mechanical system for positioning the detector and the patient.
Radioactive materials

1. Not toxic
2. Low half life
3. Appropriated energy
4. Gamma only emitter

- Tc 99m
- I 133
- Ga
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## Crystal materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/ml)</th>
<th>Relative Output</th>
<th>Decay time (ns)</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI(Tl)</td>
<td>3.67</td>
<td>1.00</td>
<td>230</td>
<td>410</td>
</tr>
<tr>
<td>BGO</td>
<td>7.13</td>
<td>0.12</td>
<td>300</td>
<td>480</td>
</tr>
<tr>
<td>BaF$_2$</td>
<td>4.89</td>
<td>0.05</td>
<td>0.6-0.8</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.15</td>
<td>630</td>
<td>310</td>
</tr>
<tr>
<td>CsF</td>
<td>4.61</td>
<td>0.06</td>
<td>2.5</td>
<td>390</td>
</tr>
</tbody>
</table>
### Crystal thickness

<table>
<thead>
<tr>
<th></th>
<th>140 keV</th>
<th></th>
<th>363 keV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3/8&quot;</td>
<td>1/2&quot;</td>
<td>3/4&quot;</td>
<td>3/8&quot;</td>
</tr>
<tr>
<td>Total efficiency</td>
<td>88%</td>
<td>94%</td>
<td>98%</td>
<td>35%</td>
</tr>
<tr>
<td>Photopeak efficiency</td>
<td>82%</td>
<td>89%</td>
<td>95%</td>
<td>24%</td>
</tr>
</tbody>
</table>
In nuclear medicine, the radiation comes from the organ not from outside, so, since the radiation is isotropic it is needed to apply a collimator. The collimator also avoid the scattered radiation to reach the detector.
Collimators

- Device used to minimize the effect of scattered radiation.
- Usually it is constructed with lead

Types:

- Parallel multihole
- Diverging
- Converging
- Slant hole
- Pinhole
Collimators

- Parallel hole
- Pinhole
- Converging
- Diverging
Light guide/PMTs/Preamplifiers
Position calculations

For a scintillation event in the crystal, the amount of light given off is proportional to the amount of energy imparted in the crystal.

This light will be detected by more than one PMT. Thus depending on how much light the PMT sees, the output signal will be different. The amount of light seen by a PMT is a function of the distance between the scintillation event and the PMT. (Except at the edges)

Thus, the closer the PMT is to the scintillation event, the larger the output signal, and conversely, the further away the PMT, the smaller the output.

The total of all output signals is proportional to the total energy deposited in the crystal by the incoming γ ray.

So if we combine the relative output signals from each PMT according to it’s XY location on the detector, we can determine the XY location of the scintillation event. This is performed with a position encoding matrix.
The output from each PMT tube is wired into a capacitor (resistance) array that determines 4 outputs signals: $X^+, X^-, Y^+, Y^-$. 

$X^+$ consists of increasing capacitance moving across the X direction.

$X^-$ consists of increasing capacitance moving in the opposite direction across the X direction. Similar for Y directions.
Difference Circuits

X position is found by the difference between the $X^+$ and $X^-$

\[ X = X^+ - X^- \]

Y position is found the same way

\[ Y = Y^+ - Y^- \]

Summing Matrix Circuit (SMC)

Total signal (equivalent to total light output)

\[ Z = X^+ + X^- + Y^+ + Y^- \]
As discussed before, the scattered radiation (incoming or produced inside the detector) is not contributing for the image and should be minimized. The collimator is reducing the incoming external scattered radiation but for minimizing the effects in the image, it is necessary also to try to eliminate the scatter produced inside the detector. This is performed by a multichannel analyzer which discriminates the pulses produced by the photons not depositing all their energies in the detector.
Pulse height analyzer

Determines the energy of the incident γ ray that interacts within the NaI(Tl) crystal. The total light produced in the scintillator is proportional to the energy of the γ photon.

Output voltage from PMTs gets summed into Z pulse. Size of the Z pulse represents the energy of the detected gamma photon.

Windowing is also done to bin energies within a certain range into energy channels → result is a histogram of measured counts/channels

Use PHA to select the photo peak of the gamma emitter we are using.
## The Gamma Camera

### History

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
</table>
| 1956 | Hal Anger at Donner Labs  
\(\frac{1}{4}\)" NaI(Tl) Crystal  
5" diameter containing 7 PMTs |
| 1960 | First commercial units available by Nuclear Chicago, Seearle and Siemens  
\(\frac{1}{2}\)" Crystal  
7" diameter containing 7 PMTs |
| 1963 | Crystal size \(\frac{1}{2}\) " thick NaI(Tl)  
11.5" diameter with 19 PMTs |
| **Now** | Crystal thickness from \(\frac{1}{4}\)" to \(\frac{3}{4}\)"  
up to 24 " diameter  
Up to 91 PMTs |
Types of Gamma Cameras

Analog – Acquisition and processing analog

Semi-digital – Acquisition analog and processing digital

Full-digital – Acquisition and processing digital

Planar

SPECT (Single photon emission computerized tomography)
Scintigraphy (SPECT): imaging device
Single Photon Emission Tomography

SPECT gives functional information
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Additional components in the SPECT GCs

- One or two heads
- Rotation of the gantry (one strong motor)
- Axial movement of the heads (two motors)
- Lifting the patient table (two or three motors)
- Movement of the pallet (one motor)
- Electrocardiogram system
Head 1 axial movement control

Heads rotation movement control

Head 2 axial movement control
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- Pallet movement control
- Table height control
Nuclear Imaging

Application to the detection of bone metastases
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PET: principles

Gamma rays
Positron Emission Tomography

PET gives functional information
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Quality control

Homogeneity

Linearity

Center of rotation (SPECT)
Homogeneity

IAEA Laboratory Seibersdorf
Serial Number : DH-612111-00

Matrix Size : 256x256x16
View ID : FLOOD TEST IM_H2
AcqDate : 04.08.2008
AcqStartTime : 14:30:00
Total Time : 788.6 secs
Sum : 14863070
Max. pix value: 480

Pixel size : 2.065000 mm
Homogeneity

Intrinsic and extrinsic

Flood phantom

Co-57 flat source
Linearity
Integral and differential

IAEA Laboratory Seibersdorf
Serial Number :DH-612111-08

Head : 

Matrix Size : 1024x1024x16
View ID : X_H1
AcqDate : 01.31.2007
AcqStartTime : 15:24:49
Total Time : 1016.9 secs
Sun : 7998171
Max. pix value : 175

Pixel size : 0.590000 mm

ESC: Go Back  ENTER:Movie On/Off  UP/DOWN:Next/Previous  PgUp/PgDn:Palette
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Resolution

Bar phantom
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NEMA Tests

```
INSTRinsic spatial linearity
(NEMA NU 1-1994.2.2)
IAEA Laboratory Seibersdorf
Serial Number : DH-612111-09

Head : 2
Isotope ID : TC-99M
Collimator ID : INTR
Flood Curr. : INTR
Matrix Size : 1024x1024x16
View ID : Y_H2
AcqDate : 04.10.2008
AcqStartTime : 16:36:20
Total Time : 304.9 secs
Sum : 15994206
Max. pix value : 379
Iris X (mm) : 531
Iris Y (mm) : 590
Iris D (mm) : 780
Fantom size (mm) : 30

CFDV Y(mm) X(mm) Aver.
ISR FWHM : 3.33 3.34 3.33
ISR FWTM : 6.51 6.54 6.52
ASL : 0.24 0.33
DSL : 0.08 0.08

UPDV Y(mm) X(mm) Aver.
ISR FWHM : 3.30 3.43 3.40
ISR FWTM : 6.64 6.74 6.69
ASL : 0.30 0.34
DSL : 0.10 0.09
```
Spatial registration

Matrix Size: 1024x1024x16
View ID: CENTER H1
AcqDate: 12.11.2007
AcqStart: 14:42:36
Total Time: 11.9 secs
Sun: 581574
Max. pix value: 1079

NMSR: 3.25 mm

MULT.-WIN. SPAT. REGISTR
X: 0.716 mm/pix
Y: 0.712 mm/pix

Central point
1-2: 0.2440 mm
2-3: 0.1076 mm
3-1: 0.3465 mm

40% UFOV
80% UFOV

X 1-2: 0.2239 mm 0.8417 mm
2-3: 0.2072 mm 1.7709 mm
3-1: 0.3113 mm 2.6120 mm

X 1-2: 0.2982 mm 1.3309 mm
2-3: 0.2513 mm 1.9221 mm
3-1: 0.5487 mm 3.2508 mm

Y 1-2: 0.0815 mm 0.6591 mm
2-3: 0.1690 mm 0.1037 mm
3-1: 0.2403 mm 0.7626 mm

Y 1-2: 0.3646 mm 0.9148 mm
2-3: 0.2553 mm 0.2526 mm
3-1: 0.5674 mm 1.1666 mm
Energy resolution

Intrinsic Energy Resolution (NEMA MU 1-1994.2.3)
IAEA Laboratory Seibersdorf
Serial Number: DH-612111-00

Head: 1
Isotope ID: Tc-99m

View ID: FWHM_H1
AcqDate: 02.01.2007
AcqStartime: 14:21:19

1. FWHM: 9.57
2. FWHM: 9.51
3. FWHM: 9.45
4. FWHM: 9.48
5. FWHM: 9.56
Average: 9.51
Maximum counting rate

Maximum count rate: 370319
Center of Rotation

Spirit DH-U u2.04

Center of Rotation
(IAEA TECHDOC 681 8.3.3.)
IAEA Laboratory Seibersdorf
Serial Number: DH-612111-00

Head: DH
Isotope ID: TC-99m
Collimator ID: LEHR
Flood Corr.: INTB
Matrix Size: 64x64x16
View ID: COR_TEST_102_DH
AcqDate: 05.31.2007
AcqStartTime: 14:22:17
Total Time: 10.0 secs
Sum: 42250
Max. pix value: 5727

<table>
<thead>
<tr>
<th>Offset</th>
<th>X offset</th>
<th>dX max</th>
<th>dX min</th>
<th>dY max</th>
<th>dY min</th>
<th>COR</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 mm</td>
<td>-0.2690</td>
<td>0.3304</td>
<td>-0.3493</td>
<td>0.2353</td>
<td>-0.5621</td>
<td>-0.5621</td>
</tr>
<tr>
<td>2 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

135 160 225 270 315 deg
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Jaczjacks Phantom
Shielding
Radiation protection

The x ray discover of x ray produced a great advance for science. Very soon after its discover some harmful effects appeared. The first victims where the physicists and medical doctors involved in the research and utilization of ionizing radiation.

In 1928 was created a commission that later generated the actual International Commission for Radiation Protection (ICRP). This commission produces guides and information for the secure use of ionizing radiation.

ICRP divided the ionizing radiation in the following way regarding the risk of a particular effect:

**Somatic stochastic** - (occurs with the irradiated person and have random nature). In these effects, the involved cells are modified by radiation but not destroyed. Later there is a possibility of producing cancer.

**Stochastic hereditary** – In these effects the cells can be damaged in a way that they will transfer modified genetic information for a descendent.

**Deterministic (non stochastic)** – In these effects the cells of an organ or tissue are destroyed and loose their function.
Quantities associated to radiation protection

A similar committee was created for defining the quantities related to radiation, the International Committee for Radiological Units (ICRU). The main quantities defined looking to associate the effects of the ionizing radiation in the human body are:

**Absorbed Dose (Unit: Gray (Gy))** - It a measure of the energy deposited by radiation in a specific tissue per unit of mass of this tissue (1 Gy = 1 J kg⁻¹).

**Equivalent Dose (Unit: Sievert (Sv))** – This quantity associates the absorbed dose to the type of radiation involved using weighting factors. In case of Gamma, X rays and Beta particles, this factors is equal to one in case of alpha particles in equal to 20, etc.

\[ H = w_T . D_T \]
<table>
<thead>
<tr>
<th>Type of Radiation</th>
<th>ICRP $w_T$ Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-rays, $\gamma$-rays, $\beta$-rays</td>
<td>1</td>
</tr>
<tr>
<td>neutrons ($E &lt; 10$ keV)</td>
<td>2 to 5</td>
</tr>
<tr>
<td>neutrons ($E = 0.01$ MeV)</td>
<td>2.5 to 10</td>
</tr>
<tr>
<td>neutrons (0.1 MeV)</td>
<td>7.5 to 10</td>
</tr>
<tr>
<td>neutrons (0.5 MeV)</td>
<td>10 to 20</td>
</tr>
<tr>
<td>neutrons (0.1 to 2 MeV)</td>
<td>20</td>
</tr>
<tr>
<td>neutrons (2 to 20 MeV)</td>
<td>5</td>
</tr>
<tr>
<td>neutrons (general)</td>
<td>10</td>
</tr>
<tr>
<td>high-energy protons, $\alpha$-particles, fission fragments, or heavy nuclei</td>
<td>20</td>
</tr>
</tbody>
</table>
Effective Equivalent Dose (Unit Sievert (Sv)) – This is the dose that once applied to the whole body will involve the same risk of mortality as if applied to a specific part of the body. In this case, in addition to the weighting factor for the involved radiation, other weighting factor are applied for each organ or tissue.

<table>
<thead>
<tr>
<th>Organ or tissue</th>
<th>Weighting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonads</td>
<td>0,20</td>
</tr>
<tr>
<td>Bone marrow (red)</td>
<td>0,12</td>
</tr>
<tr>
<td>Lungs</td>
<td>0,12</td>
</tr>
<tr>
<td>Stomach</td>
<td>0,12</td>
</tr>
<tr>
<td>Liver</td>
<td>0,05</td>
</tr>
<tr>
<td>Thyroid</td>
<td>0,05</td>
</tr>
<tr>
<td>Skin</td>
<td>0,01</td>
</tr>
</tbody>
</table>
The effective equivalent dose is calculated as:

\[ E = \sum W_T D_T w_T \]

Where: \( W_T \) is the weighting factor for the organ or tissue involved, 
\( D_T \) is the absorbed dose in the organ or tissue involved, 
\( w_T \) is the weighting factor for the radiation type.
Main cares to have when working with ionizing radiations:

**Distance** - To be as further as possible from the radiation source;

**Time** – To be exposed to radiation for the lowest time as possible;

**Shielding** – To use shielding (lead for example) (walls, gloves, etc);

**Area** – To use the smallest radiation beam as possible (in area);

**Simulators** - To apply test instruments and simulators for calibration and adjustment, never use the body for checking or calibrating radiation.