Basic Principles of Scintillation Cameras

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Disclosures to Report: Honoraria--Corscan
Gamma Camera

Patient → Gamma camera → Computer → Digital image

Lead colimator → Scintillating crystal → Light detectors

Gamma camera:
- Patient
- Gamma camera
- Computer
- Digital image

Computes x and y location of gamma ray
Gamma Camera
Detector Components

Pre-amps
PMT’s
Light Pipe & NaI Crystal
Aluminum cover sheet
Positioning Pulse

Positioning arithmetic refers to the electronic scheme used to determine the location of the light pulse emitted when a $\gamma$-ray is absorbed in the NaI crystal.
**γ-Ray Localization (2-dimension)**

<table>
<thead>
<tr>
<th>Source</th>
<th>NaI Crystal + PMT's</th>
<th>Voltage output</th>
<th>Cathode ray tube</th>
</tr>
</thead>
</table>

![Diagram of γ-Ray Localization](image)

- **Output Representation:**
  - ADC: $X = 10100111$
  - $Y = 11010010$
Positional Arithmetic: 2-D

\[ x^+ - x^- = x \text{ position} \]
\[ y^+ - y^- = y \text{ position} \]

Location of \( \gamma \)-ray on NaI crystal

P.M. tubes

Electronic Circuit to sum signals from the PMT's
System Corrections

All $\gamma$-cameras exhibit a non-uniform response to radiation over their field of view.

Following corrections are applied to adjust for these non-uniformities:

- Energy Correction
- Linearity Correction
- Uniformity Correction
Gamma Camera

Energy Correction

Energy window

Raw combined energy peaks

Aligned energy peaks

Photopeak alignment
Energy Correction
Effect on Energy Resolution

Improved Energy Resolution
⇒ Better separation of Photopeaks
Energy Correction

Effect on Image Uniformity

Flood image without energy correction

Flood image with energy correction

Energy correction
A PMT has a non-linear response to light across the face of the tube.

There is increased sensitivity to light at the edge of the tube compared to the center.

Consequently, events near the edge of the PMT are mis-positioned towards the center of the tube.
Linearity Correction

Effect on Image Uniformity

Flood image uncorrected

Linearity correction

Flood image corrected
Linearity Correction

- Acquire a high-count image of a suitable phantom (e.g. orthogonal hole phantom)
- Compute the X and Y differences between the true and measured locations of the holes in the phantom
- Store these differences in a linearity correction map
- Correct all detected events “on-the-fly” using the correction map to relocate events to their true position
Uniformity Correction
Matrix Multiplication

A typical scheme for uniformity correction using matrix multiplication is described below:

1. Acquire a high count flood image
2. Measure the average counts per pixel \( (P_{avg}) \)
3. For each pixel, compute a correction factor \( = P_{avg} / P \)
4. Store corrections as a uniformity correction map
5. Correct clinical studies by multiplying each pixel in the clinical image by its corresponding pixel in the correction map.
Uniformity correction is generally used after application of both energy and linearity correction. It is not designed to correct for major non-uniformities in the field of view.
Correction Maps

Effect on Image Uniformity

The following gives an indication of the effects of each type of correction on the intrinsic uniformity of the gamma camera.

<table>
<thead>
<tr>
<th>Correction</th>
<th>Uniformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>20%-30%</td>
</tr>
<tr>
<td>Energy</td>
<td>20%-30%</td>
</tr>
<tr>
<td>Energy + Linearity</td>
<td>5%-10%</td>
</tr>
<tr>
<td>Energy + Linearity + Uniformity</td>
<td>2%-5%</td>
</tr>
</tbody>
</table>
Summary: The $\gamma$-Camera

- Basic principles unchanged for > 40 years

- New digital detectors offer advantages over older analog systems in several areas
  - Better correction techniques
  - More stable performance

- Future $\gamma$-cameras may employ materials other than NaI (e.g. LSO) or be based on semiconductor detectors (e.g. CZT)
PET: Positron Emission Tomography
Coincidence Detection

511 keV $\gamma$

Rb-82

511 keV $\gamma$

6 ns

Coincidence Imaging
# Physical Characteristics of Scintillation Crystals

<table>
<thead>
<tr>
<th></th>
<th>LSO</th>
<th>GSO</th>
<th>BGO</th>
<th>NaI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density (g/cc)</strong></td>
<td>7.4</td>
<td>6.7</td>
<td>7.1</td>
<td>3.6</td>
</tr>
<tr>
<td><strong>Effective Z</strong></td>
<td>66</td>
<td>59</td>
<td>75</td>
<td>51</td>
</tr>
<tr>
<td><strong>Mean Free Path (cm)</strong></td>
<td>1.16</td>
<td>1.43</td>
<td>1.05</td>
<td>2.88</td>
</tr>
<tr>
<td><strong>Decay Constant (nsec)</strong></td>
<td>40</td>
<td>60</td>
<td>300</td>
<td>230</td>
</tr>
<tr>
<td><strong>Relative Light Yield</strong></td>
<td>75</td>
<td>25</td>
<td>20</td>
<td>100</td>
</tr>
</tbody>
</table>

- **Stopping power** => low mean free path, detector efficiency
- **Decay constant** => small value reduces ‘randoms’, improves sensitivity
- **Relative light yield** => high values improves energy resolution, reduce scatter
Coincidence Detection

- Annihilation photon pairs are detected by opposing scintillation detectors
- If 2 photons are detected ‘simultaneously’, annihilation must have occurred along a line connecting the detectors
- Coincidence events from all angular and linear positions are stored in a computer
- Reconstruction software generates images depicting the localization and concentration of the radioisotope within the region of the body that was scanned

\[ e_2 - e_1 < 'CW' \]
PET: Four types of photon events

**Bad events**

- **Singles**: These are individual photons that do not have a companion photon. They have a negative impact on the dead time of the system.

- **Scatter**: These are paired photons that do not have a companion photon. They reduce the contrast of the final image. Scatter compensation is needed to correct for these.

- **Randoms**: These are pseudo “paired” photons caused by the chance correlation of two singles photons. Randoms compensation is needed to correct for these.

**Good event**

- **Trues**: These are true “paired” photons. These photons are used for creating the photopeak distribution.
ATTENUATION CORRECTION
Basic Principles

Acquire a Transmission Scan
1. External Radionuclide Source
2. CT
3. Emission Scan

Emission  Scatter  Transmission
ATTENUATION CORRECTION CHARACTERISTICS

- TRANSMISSION MAP
- SCATTER MAP
The $\gamma$-Camera Collimator
The collimator strongly affects

Field of View
Spatial Resolution
Sensitivity
Image Distortion
**γ-Camera Collimation**

Collimator designed to limit (by attenuation), the detection of γ-rays to those rays travelling in certain directions.

Collimator material must be composed of a dense material with a high-atomic number (e.g. lead).
The parallel-hole collimator is the most common collimator design and consists of an array of parallel holes separated by thin septa.

All holes are of identical shape and orientation with parallel septal walls.

The parallel-hole collimator gives a one-to-one ratio between the size of the isotope distribution and the size of the image (i.e. no magnification or minification)
Typical Collimator Design
Parameters

**LEGP Collimator**

Average Values
LEGP collimator
- $L = 2.5$ cm
- $d = 2-4$ mm
- $\lambda = 0.1-0.3$ mm
The Parallel-hole Collimator

Collimator response to radiation

Geometric component
Penetration component
Scatter Component

γ-Ray Source
Collimator NaI
Parallel-Hole Collimators

Parallel Hole Collimators can be classified by the following parameters:

- Energy
- Spatial Resolution
- Sensitivity
Low-Energy Parallel-Hole Collimators

Collimator design is a trade-off between resolution and sensitivity. Possible options:

- Low Energy High Resolution (LEHR)
- Low Energy All Purpose (LEAP)
- Low Energy High Sensitivity (LEHS)

High Resolution = Low Sensitivity
High Sensitivity = Low Resolution
System resolution ($R_s$) is a function of both Collimator resolution ($R_c$) & Intrinsic resolution ($R_i$)

$$R_s^2 = R_c^2 + R_i^2$$

Typical values:
- $R_c = 8$ mm
- $R_i = 3$ mm
- $R_s = 8.5$ mm
Collimation: Resolution vs. Distance

![Graph showing resolution vs. distance for different collimators.](image)

- **General Purpose Collimator**
  - Resolution: Linear increase with distance
  - Imaging Range for Clinical Studies

- **High Resolution Collimator**
  - Resolution: Linear increase with distance
Parallel-Hole Collimator
Sensitivity vs. Distance

Counts/hole decrease as $1/d^2$
Number of holes transmitting counts increase as $d^2$

Single-hole efficiency $\propto 1/d^2$

Detector area exposed $\propto d^2$
Non-Standard Collimators

- Slant Hole collimators
- Diverging collimators
- Converging collimators
- Pinhole collimators
- Fan-beam collimators
- Cone-beam collimators
- Miscellaneous
Miscellaneous Collimators

Tungsten / Tantalum collimators

Parallel hole collimators manufactured from materials other than lead.

Higher densities yield improvement in sensitivity for same resolution.

May be useful in certain types of clinical studies where the characteristic x-rays produced by lead are a problem.
Collimator Resolution

**Very Important !!!**

For all types of collimation, resolution degrades as the object is moved away from the collimator face.
Collimator Sensitivity

- Collimator sensitivity is affected by Energy window setting Type of collimator

- Typical values
  - LEGP Collimator = 300 cts/min/µCi
  - LEHR Collimator = 150 cts/min/µCi

- Change in sensitivity indicates problem with detector head, not collimator.
## Summary: Collimation

<table>
<thead>
<tr>
<th>Collimator Parameter</th>
<th>Resolution</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole Diameter</td>
<td>Decrease</td>
<td>Increase</td>
</tr>
<tr>
<td>Hole Length</td>
<td>Increase</td>
<td>Decrease</td>
</tr>
<tr>
<td>Septal Thickness</td>
<td>/ No change</td>
<td>Decrease</td>
</tr>
<tr>
<td>Source-Collimator Distance</td>
<td>Decrease</td>
<td>/ No change</td>
</tr>
</tbody>
</table>
Quality Control
Gamma Cameras

- Definition of Terms
- Gamma Camera Uniformity
- Spatial Resolution
- Spatial Linearity
- Sensitivity
- Energy Resolution
- Evaluation of Collimators
- Summary and Conclusions
Most gamma cameras exhibit non-uniformity or distortions at the edge of the detectors field of view.

Measurements of system performance are therefore usually limited to a region slightly smaller than the full field of view.

**UFOV - Useful Field of View:**
Defined as the circle or rectangle that encloses ~95% of the detector field of view

**CFOV - Central Field of View:**
Defined as 75% of the UFOV
Definition of Terms – Uniformity

Uniformity refers to the ability of a gamma camera to display a uniform response to radiation over its field of view.

The non-uniformities in a gamma camera can be described by 2 parameters:

Integral Uniformity
Differential Uniformity
Integral Uniformity defines the greatest variation in uniformity over the field of view of the gamma camera. Can be defined for the UFOV and CFOV.

Uniformity image must be
- Analyzed in a 64 x 64 matrix
- Smoothed with 9-point smoothing filter (to reduce statistical noise)
- Defined by following equation
  \[ \text{Int. Unif.} = \frac{\text{Max ct} - \text{Min ct}}{\text{Max ct} + \text{Min ct}} \]
Integral Uniformity

Integral Uniformity

= 5.6 % (UFOV)
= 4.7 % (CFOV)

Integral Uniformity

= 12.5 % (UFOV)
= 10.6 % (CFOV)
Differential Uniformity defines the greatest variation in uniformity over a small portion of the field of view of the gamma camera. Can be defined for the UFOV and CFOV.

Uniformity image must be:
- Analyzed in a 64 x 64 matrix
- Smoothed with 9-point smoothing filter (to reduce statistical noise)
- Measured as for Integral Uniformity, but only over a small (~5 pixel) region of the field of view
- Process repeated over multiple regions to cover entire UFOV or CFOV
Differential Uniformity

Gamma Camera Field of View

Integral Uniformity
\[ \frac{(2350 - 1924)}{(2350 + 1924)} = 9.9\% \]

Differential Uniformity (X-dir.)
\[ \frac{(2270 - 2100)}{(2270 + 2100)} = 3.9\% \]

For each row of a 64 x 64 matrix, there are 64 measurement of Differential Uniformity. Process is repeated for all 64 rows. Highest value of the 4096 calculations is reported as Diff Unif (X-dir). Process is then repeated for columns (Y-dir).
Measurement of Intrinsic Uniformity

Procedure

- Set orientation to standard position
- Place point source at a distance = 4 UFOV size and centered over the middle of the detector
- Set energy window to width normally used for clinical studies (e.g. 20%) and centered on photopeak
- Ensure that count rate < 20,000 counts / sec. For newer systems, higher count rates may be acceptable.
- Acquire a uniformity image containing ~ 2 Mcts
- Record all settings and duration of acquisition
Quality Control
Gamma Cameras

- Definition of Terms
- Gamma Camera Uniformity
- Spatial Resolution
- Spatial Linearity
- Sensitivity
- Energy Resolution
- Summary and Conclusions
Measurement of Spatial Resolution

Procedure

- Can be measured intrinsically or extrinsically
- Numerous types of test patterns available
- Test pattern should assess resolution in both the X and Y-direction
Measurement of Spatial Resolution

Bar Phantoms

- 4-quadrant bar phantom (used in 90% of labs)
- Parallel Line Equal Spacing (PLES) Phantom
- Hine-Duley Phantom
- Orthogonal-hole Phantom
Evaluation of Spatial Resolution

- Results are qualitative only!
- Note minimal resolvable line / bar spacing
- Check for variations throughout the field of view
- Compare results with those obtained during acceptance testing of the system
Quality Control

Gamma Cameras

- Definition of Terms
- Gamma Camera Uniformity
- Spatial Resolution
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- Sensitivity
- Energy Resolution
- Summary and Conclusions
Spatial Linearity

- Normally measured with spatial resolution (same protocol)
- Can be evaluated from most test pattern images
- More sensitive to changes in system performance than resolution
Spatial Non-Linearity

Poor linearity correction: older gamma cameras often exhibit good linearity in the center of the field of view, but show distortion near the edges of the field of view.
Quality Control
Gamma Cameras

- Definition of Terms
- Gamma Camera Uniformity
- Spatial Resolution
- Spatial Linearity
- Sensitivity
- Energy Resolution
- Summary and Conclusions
Quality Control
Sensitivity

- Acquire an Image for Uniformity
- Record
  - Total Counts
  - Total Time
  - Activity of Source
- Calculate Sensitivity in Units of cts/min/µCi
Quality Control
Gamma Cameras

- Definition of Terms
- Gamma Camera Uniformity
- Spatial Resolution
- Spatial Linearity
- Sensitivity
- Energy Resolution
- Summary and Conclusions
Measurement of Energy Resolution

- Acquire an energy spectrum of the isotope of interest under scatter-free conditions
- Measure the FWHM of the principal photopeak
- Requires that gamma camera system has the capability for display and analysis of the energy spectrum
Measurement of Energy Resolution

Counts (%)

Energy (keV)

FWHM = 12.2 keV
= 8.7 %
Quality Control
Gamma Cameras

- Definition of Terms
- Gamma Camera Uniformity
- Spatial Resolution
- Spatial Linearity
- Sensitivity
- Energy Resolution
- Summary and Conclusions
<table>
<thead>
<tr>
<th>Test</th>
<th>Recommended Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniformity</td>
<td>Daily</td>
</tr>
<tr>
<td>Resolution</td>
<td>Weekly</td>
</tr>
<tr>
<td>Linearity</td>
<td>Weekly</td>
</tr>
<tr>
<td>Collimator check</td>
<td>Every 3 months</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Yearly</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>Yearly</td>
</tr>
<tr>
<td>Count Rate Performance</td>
<td>Yearly</td>
</tr>
</tbody>
</table>
Quality Control Testing of SPECT Systems
High quality SPECT requires that all aspects of the tomographic system be functioning correctly and that the operator understand the potential problems that may occur with any tomographic system.
QC of Tomographic Systems

- Uniformity
- Center of Rotation
SPECT Ring Artifacts
How they are Generated

Planar Image @ 0°

Row of pixels

Transaxial Slice

Uniformity Defect
SPECT Ring Artifacts
How they are Generated

Artifact changes from square to circle as the number of views increases
Ring Artifacts
Concentric with Center of Matrix

Tc-99m Sestamibi Myocardial Perfusion Study

Unzoomed Transaxial Slice
QC of Tomographic Systems

- Uniformity
- Center of Rotation
Center of Rotation (CoR)

Gamma camera rotating about a point source of activity

Image of point source seen on detector
Center of Rotation (CoR)

The Center of Rotation is that central point in space about which the detector head rotates.
Center of Rotation (CoR)

The Center of Rotation is constant as a function of angle of rotation.

The Center of Rotation is constant as a function of angle of rotation.
Measurement of Center of Rotation

Methods

- Tc-99m Point Source (~100 µCi)
- Radius of rotation ~ 20 cm
- Std. 360 degree COR acq. / analysis
- Use manufacturer's analysis software

Results

- Very stable parameter
- Change in COR due to
  - Operator error
  - Mechanical shift in gantry
  - Older systems - X/Y Gain problem
  - Collimator hole alignment
Center of Rotation Analysis

- Center of Rotation - checked weekly
- For a 64 x 64 matrix, true value = 32.5
- For a 128 x 128 matrix, true value = 64.5
- CoR should not vary by more than 3 mm equivalent to ~0.5 pixel for a 64 x 64 matrix or ~1 pixel for a 128 x 128 matrix
Center of Rotation Analysis

<table>
<thead>
<tr>
<th>Average X Center Of Rotation</th>
<th>Max - Min X COR</th>
<th>Average Y Position</th>
<th>Y Position Max - Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.256</td>
<td>0.075</td>
<td>31.340</td>
<td>0.225</td>
</tr>
</tbody>
</table>
Center of Rotation Error

Transaxial Slice: TI-201 Myocardial Perfusion Study

COR error best seen in Transaxial Images
Center of Rotation Error

Center of Rotation errors are:

- Consistent from study to study
- Best seen on transaxial data
- Are more difficult to recognize on multi-head systems
Summary

- Routine QC (uniformity / COR) will detect most potential problems.

- Older system (> 5 years) exhibit more problems with gantry and collimator alignment.

- Artifacts in SPECT may be subtle and difficult to recognize.