Basic Physics, Instrumentation and Quality Control in PET Fusion Imaging

- Nathaniel B. de Vera, M.Sc.
Objectives:

- Introduce multi-modality (PET/CT, SPECT/CT) fusion imaging
- Describe difference between ACD and ToF
- Describe QC activities
What is fusion imaging?

- Theoretically, any type of medical image can be combined or fused with any other type to create a third image.

What is PET/CT?
PET-CT System

PET-CT is not simply combined with PET and CT. PET-CT is the system integrated hardware, software and applications.

\[
\text{PETCT} \neq \text{PET+CT}, \quad \text{PETCT} \overset{\text{CT}}{\int}_{\text{PET}} (\text{PET+CT})dt
\]
PET/CT Benefits

- Improved tumor detection
- Precise staging of disease
- Better monitoring of cancer recurrences
- Max. sensitivity through 3-D acquisition
- Excellent image quality and spatial resolution
- Shorter investigation time
- Patient convenience of a single scan
- Convenient fusion with CT and MRI for diagnosis and treatment
Basic Principles of PET
Basic Principles of PET

Annihilation

Neutron deficient isotope

511 keV γ-ray

Emission is on straight line

511 keV γ-ray
Random events: invalid

**Problem:** Random events equal and exceed true events

**Consequences:** Reduced contrast and Reduced accuracy

**Solution:** Measure random events (delayed coincidence window) and Reduce coincidence time window
Scatter events: invalid

Problem: Scatter is patient geometry dependent and can exceed 50%.

Consequences: Reduced contrast and Reduced accuracy

Solution: Measure scatter
Basic Principles of PET
SPECT vs. PET

SPECT/Planar Imaging
- different isotopes have different photon energies
- tracer emits a single photon
- photon contributes to image if it falls into energy range
- image shows tracer distribution

PET Imaging
- different isotopes have same photon energy
- tracer emits two photons
- photons contribute to image both fall into energy window and also fall into timing window (i.e. coincidence)
- image shows tracer distribution
Scanner Design & Configuration
State-of-the-art PET/CT

- Bore size: 70 cm for immobilization devices and large pts.
- Axial length: 100 cm
- CT can be dual or multi-slice, w/ axial or helical acquisition modes and different rotation speeds
Basic Principles of PET

PET Equipment

1) Gantry with the patient port and detecting system

2) Patient bed

3) Electronics for data processing and scanner control

4) Operator console
Basic Principles of PET

PET detectors

Detector block

PMT

Lightguide

A

B

D

Channeled scintillation light
New PET/CT Design Challenges

Inconsistent image quality between patients of different sizes

This is a documented issue with all PET systems:

• For an equivalent data signal to noise ratio, a 120 kg person would have to be scanned 2.3 times longer than a 60 kg person

• 5 min/bed position scans are sufficient for optimal lesion detection with LSO PET/CT in obese patients

Optimizing Injected Dose in Clinical PET by Accurately Modeling the Counting-Rate Response Functions Specific to Individual Patient Scans. Charles C. Watson, PhD et al Siemens Medical Solutions Molecular Imaging, Knoxville, Tennessee, JNM Vol. 46 No. 11 1825-1834, 2005

Optimizing Imaging Protocols for Overweight and Obese Patients: A Lutetium Orthosilicate PET/CT Study. Halpern, et al, UCLA David Geffen School of Medicine, Los Angeles, California, JNM Vol. 46 No. 4 603-607, 2005
Basic Principles of PET

Time of Flight

- Utilized to improve the signal to noise ratio in PET images, by reducing the noise propagation along the line of response (LOR) during projection in image reconstruction.

Figure taken from:

- Data reconstructed without (top) and with (bottom) TOF information.
Time-of-Flight

Basic Concept

Coincidence and backprojection

Timing within coincidence window
**Time-of-Flight vs. Conventional PET**

*Better information sent to reconstruction*

- **Conventional PET Image Formation**
- **Time-of-Flight Image Formation**

*More precise localization of annihilation event improves image quality*
Time-of-Flight

Effect of System Timing Resolution

Conventional PET Image Formation

1 ns ToF Image Formation

TruFlight (~650 ps) Image Formation

System timing resolution defines performance benefit of time-of-flight
Time-of-Flight

TruFlight Imaging Benefits

Data courtesy of J Karp, University of Pennsylvania

3D RAMLA  Line of Response  Time-of-Flight

Time-of-flight improves image quality
TruFlight Time-of-Flight

left upper quadrant peritoneal node

114kg (251lb) patient with colon cancer

Data courtesy of J Karp, University of Pennsylvania
Note: Acquisition times and phantom activities are less than those prescribed by the NEMA NU 2-2001 standard in order to more closely represent clinical imaging conditions. Therefore results are not directly comparable to NU 2-2001 results.
<table>
<thead>
<tr>
<th>Property</th>
<th>LSO</th>
<th>LYSO</th>
<th>GSO</th>
<th>BGO</th>
<th>LuAP</th>
<th>LaBr₃</th>
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</thead>
<tbody>
<tr>
<td>Density</td>
<td>7.4</td>
<td>7.1 (10% Y)</td>
<td>6.7</td>
<td>7.1</td>
<td>8.3</td>
<td>5.3</td>
</tr>
<tr>
<td>Effective Z</td>
<td>66</td>
<td>64</td>
<td>57</td>
<td>75</td>
<td>66</td>
<td>47</td>
</tr>
<tr>
<td>Attenuation length</td>
<td>1.15</td>
<td>1.2</td>
<td>1.4</td>
<td>1.04</td>
<td>1.04</td>
<td>2.1</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>~11%</td>
<td>~10%</td>
<td>~10%</td>
<td>&gt;13%</td>
<td>7-9%</td>
<td>3%</td>
</tr>
<tr>
<td>Light Yield</td>
<td>1.0</td>
<td>1.2</td>
<td>&lt;0.5</td>
<td>&lt;0.2</td>
<td>~0.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Decay Time</td>
<td>~40 ns</td>
<td>~40 ns</td>
<td>60 ns</td>
<td>300 ns</td>
<td>17 ns</td>
<td>35 ns</td>
</tr>
<tr>
<td>Timing Resolution (two crystals in coincidence)</td>
<td>~450 ps</td>
<td>&lt;450 ps</td>
<td>Not optimal performance for time of flight</td>
<td>Not suitable for ToF</td>
<td>500ps</td>
<td>&lt;400ps</td>
</tr>
</tbody>
</table>

The rest of the system design must maintain as much of this intrinsic timing resolution as possible!
Scintillator: LYSO
- Selected because of timing resolution, stopping power & availability

Geometry: 4x4x22 mm
- 4x4mm selected for better spatial resolution (as compared to 4x6 mm)
- 22 mm selected as optimal balance between resolution, sensitivity and cost
- PIXELAR detector design
- Selected for better 3D performance and better energy resolution
PMT choice critical to timing resolution & stability

Conventional PMTs are not suitable for ToF imaging
  - flat cathode delivers non-uniform timing response
  - unacceptable loss in timing resolution

Uniformity of timing response across tube ( = among crystals) is critical to preserve system timing resolution, requires curved cathode
TruFlight
Electronics – Speed & Accuracy

Designed for Timing Accuracy

- **25 psec** time stamp for accurate data sampling

- **ToF Timing Resolution** – 650 psec
  - Crystal: 450 psec
  - PMTs: 100 psec
  - Other: 100 psec – electronics design plays a key role in preserving the timing resolution
### GEMINI TF Performance Measurements

<table>
<thead>
<tr>
<th></th>
<th>Transverse Spatial Resolution @ 1cm (NEMA NU 2-2001) With Line of Response</th>
<th>Axial Spatial Resolution @ 1cm (NEMA NU 2-2001) With Line of Response</th>
<th>Peak NECR (NEMA NU 2-2001)</th>
<th>Clinical NECR</th>
<th>System Sensitivity – center (NEMA NU 2-2001)</th>
<th>System Energy Resolution</th>
<th>3D Scatter Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.7 mm 4.3mm</td>
<td>4.7 mm 4.3mm</td>
<td>105 kcps @ 16 kBq/ml</td>
<td>60 kcps @ 5.3 kBq/ml</td>
<td>7000 cps/MBq</td>
<td>12%</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&gt;210 kcps @ 16 kBq/ml</td>
<td>&gt;120 kcps @ 5.3 kBq/ml</td>
<td>&gt;14,000 cps/MBq</td>
<td>12%</td>
<td>30%</td>
</tr>
</tbody>
</table>

**Industry leading PET performance BEFORE Time-of-Flight,**

**Time-of-Flight takes performance to the next level**
Proven Diagnostic Confidence of Brilliance CT

64-channel CT configuration for exceptional cardiac performance

Images Courtesy of Montefiore Medical Center (NY)
Why use CT?
CT provides images that are anatomic in nature but not functional or metabolic.

CT uses x-rays to give size, location of tumor, mass, etc.
CT doses

1 – 3 mSv head scans

5 – 20 mSv abdominal depending on the extent of scan, exposure factors *

Low dose CT: 2 – 5 mSv

Diag. CT: 14 – 20 mSv

Platten, Brix, et al
Image Comparison with CT AC and Ge AC

CT AC

Ge AC (1 min)
Image Comparison with Transmission Time

1min 18Mcount
2min 36Mcount
3min 54Mcount
5min 90Mcount
20min 360Mcount

CT10mA
CT100mA
Image Comparison with Low mAs CT AC

38mAs

19mAs

4mAs

μ-Map

PET

SUV: 5.6

SUV: 5.8

SUV: 5.9
Gantry of PET-CT

Patient Table
CT Assembly

Detector module

ceramics scintillator + photo diode array
X-ray Tube for CT

Performix TUBE made by GE

Max. Scan Time at 120kV/250mA: 110 sec
Image Acquisition

- CT scout scan (anatomic reference for PET/CT)
- CT scan (100-140 kVp at various amp)
- PET scan (3-5 min/ bed)
Dose to patient from exam:

FDG – CT dose: ~ 25 mSv
Quality Control Procedures for PET* and PET/CT** Systems

*GE Advance Nxi PET Scanner and
**Philips Gemini TF 64s PET/CT Scanner
Quality Control on PET System

- Blank Scan
  - Generates a sinogram as an output
Normal sinogram
Artifacts on sinogram

- Black bands
- Butterfly artifact
Black bands
Butterfly artifact

- Appears when the bed is loaded inside the gantry on blank scan.
- Blank scan should be repeated after the bed has been retracted away from the gantry.
Quality Control on PET/CT Systems

- Composed of QC procedures done on CT and PET acquisition gantries
- CT QC on *PET/CT-Systems* is similar to CT QC systems done on *CT-systems*
Quality Control on CT Systems

- Tube warm up/tube conditioning
- Air calibration
- Image Quality check (head Scan)
- Noise and Artifact test (body scan)
Tube conditioning

- Done prior to air calibration
- Tube conditioning is used to warm up the CT Tube after being idle overnight or longer
- A prompt will appear if the conditioning has been completed successfully or failed
Air Calibration

- Room temperature should be maintained based on the manufacturer’s recommendation (20-23 deg. Celsius)
- An image will initially appear to be assessed before the air calibration is initiated
Normal Air Calibration
Ring artifact on Air Calibration

- Ring artifacts caused by detector problems, temperature changes
Ring artifact images
Image Quality Check

- Also called the Head scan
- Done daily by setting the phantom on the bed
- Automatic test will be initialized
- PASSED or FAILED message will be displayed after the test
Noise and Artifact test

- Also called the body scan
- Done with the phantom loaded on the bed
- Absorption reading is checked
  - Teflon pin 890 $\pm$ 50 CT
  - Water hole 0 $\pm$ 4 CT
  - ROI area 14000 $\pm$ 1000 mm$^2$
QC on PET Systems

- PET daily QC
  Includes: full system initialization; baseline collection; calibration of PMT gains; Energy test and analysis; timing test; hardware and sensors test and emission collection and analysis
- at the end of each test, the system displays a PASS, WARNING or FAILURE message
Errors on PET QC

- Alignment of the test source Na-22
- Errors on the system itself i.e. detector errors
Artifacts observed during/after scanning

- PET image artifacts
  - Motion artifacts
  - Breathing artifacts
  - Extravasation
Artifacts observed during/after scanning

- CT image artifacts
  - Lines and streaks
  - Ripple and ring artifacts
  - motion artifacts
  - breathing artifacts
  - Foreign object
Artifacts observed during/after scanning

- PET/CT artifacts
  - Misregistration/ incongruence
  - Heart beat artifacts
  - Bladder filling
  - Motion
PET Artifacts

- motion
PET Artifacts

- breathing
PET Artifacts

- extravasation
PET/CT Artifacts

- Foreign object (dentures)
CT artifacts

- Lines and streaks caused by prosthesis and dentures
CT artifacts

- Ripples and rings artifacts caused by photostarvation
CT artifacts

- Heart Motion artifacts
CT artifacts

- Breathing artifacts
CT artifacts

- Foreign objects (prosthesis – hip replacement)
PET/CT artifacts

- Mis-registration

MISREGISTRATION

- Lesion mislocalisation
- Pseudopathology
- Misleading SUVs
PET/CT artifacts

- Bladder filling
PET/CT artifacts

- Motion artifacts
Motion misregistration
PET/CT artifacts

- Heart beat artifact
QA/QC of SPECT Systems
QA or QC?

- Quality Assurance is defined as the closeness with which the outcome approaches an ideal.
- Quality Control is referring to the measures to attain one particular aspect of the procedure is satisfactory.
What do I need?

- Flood Phantom or Co-57 sheet source
- SPECT phantom
- Tomographic point source(s)
Tests to be performed

- Center of rotation and alignment of axes
- Reconstructed Image uniformity
- Reconstructed spatial resolution w/ & w/o scatter
- System volume sensitivity
Center of Rotation (COR)
Purpose:

- To confirm a mirror image at 0 & 180 degrees to determine if the detector can observe the same set of parallel lines at 0 & 180 degrees
Materials needed:

- Tc-99m point source prepared according to manufacturer’s instructions
- Collimator
Technique:

- Arrange a 20% window
- Position source slightly off-center, ~ 5cm
- Arrange a 15 cm orbit
- Acquire a 360° image; use matrix size for imaging; > 32 proj.;
- < 20,000 cnts/proj.
Data Treatment:

- Compute the COR using algorithm of manufacturer
- Compare result with recommended limits
Key Points:

- Mechanical alignment check should use carpenter’s level; circular bubble levels are inadequate.
Key Points:

- Any deviation can result from: a. detector not completing circular orbit b. wrong collimator c. weight of the detector/collimator
- Motion expected along x-axis
- If motion in y-axis, due to: a. mech’cal alignment of detector b. rotation of detector w/in gantry c. angulation of collimator holes in slant-hole collimator
Weekly tests

- Centre of Rotation (COR)
  - is the detector where the software thinks it is?
COR Error - clinical effect

- Data are smoothed in a “circular” direction
- Artefacts may have a “comet tail” or ring like appearance

Corrected Data

+ 3 pixels COR error

- 3 pixels COR error
- Follow manufacturers protocol.
- Ideally, correct for all collimators used for SPECT.
- Variable angle heads checked in all configurations
- Specific corrections for some isotope / collimator combinations
Uniformity
Purpose:

- To check on non-uniformities since any of these will produce a circular effect
- However, ring artifacts can also be seen extrinsically in collimator defects, poor statistics, incomplete mixing of flood phantom
Materials needed:

- Co-57 sheet source or
- 20 mCi Tc-99m filled cylindrical phantom or
- 10 mCi Tc-99m flat disc flood phantom
- Collimators
Technique:

- Arrange a 20% window
- Attach collimator
- At a rate not greater than 30 kcps, acquire a 30 M cnt uniformity correction flood on a 64 x 64
- Correct for non-unif.
- Repeat for other collimators
Data Treatment:

- Determine non-uniformity by visual inspection
- Evaluate integral and differential uniformity by computer program
Key Points:

- Flood image of 30 M cnts on a 64 x 64 is ok
- Flood of 30 M for 128 x 128 should be smoothed
- line artifacts in collimator made during manufacturing process
- water-filled phantoms tend to bulge at center
- must acquire appropriate counts to reduce ring artefacts in highest count studies.
- 10,000 counts per pixel
  - 30 million - 64 x 64 matrix
  - 120 million - 128 x 128 matrix

High count phantom study showing slight ring artefact-OK for clinical use.

- Frequency depends on system stability
- Low count flood
  - Tc99m intrinsic or extrinsic / or Co57 extrinsic
  - Integral and differential uniformity
  - 3-5 M counts
• “Other” isotopes - recent evidence of uniformity

• Narrow Energy Windows (Tc99m)

20% window  15% Window  10% window

• Asymmetric Energy Windows (Co-57)

Peak - 10%  On Peak  Peak + 10%
Reconstruction System
Spatial Resolution
Purpose:

- To answer the question: "What size of lesion can I see with this system?"
Materials needed:

- 10 -20 mCi Tc-99m
- Jasczczak or Nuclear Associates cylindrical phantom
Jaszczak performance phantom (and others) commercially available.
Anthropomorphic Torso Phantom™

Hoffman 3-D Brain Phantom™

DATA SPECTRUM CORPORATION
A Worldwide Leader in
Medical Imaging Phantom Design™
Technique:

- Arrange a 20% window
- Attach collimator
- Accumulate 30 M cnt on 64 x 64
- Set ideal radius for orbit
- Set time per stop
Data Treatment:

- Reconstruct with Ramp
- Repeat for all acquisitions using other filters and note which work best under some conditions
Key Points:

- Hot lesions in cold field simulate brain & bone scans
- Cold lesions in hot fields simulate lung & liver scans
- Comparisons should help which filter to use for some conditions
Resolution Aspects

- Circular or non-circular orbit
- 180° (heart, liver, spleen)
- or 360° (lungs, kidneys, brain)
- Controversy centers on spatial resolution, geometrical distortion, attenuation correction
- Satisfactory completion of all procedures involved in acceptance of planar system
- Any defect in planar is magnified in SPECT
Conclusions:

- Equipment and procedures evolving rapidly (?).
- QC tests, documentation needs review.
- Specialised analysis tools required to manage changes.
- SPECT software QC identified as an area for attention.
Thank you and MABUHAY!
Thank You
and Mabuhay!