Multimodality PET/CT Imaging

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Types of Images

René Magritte *The Treachery of Images* 1928
Types of Images: Projection Imaging
Types of Images: Tomography

- Tomographic acquisition
- Reconstruction of multiple images
- Image processing: simple and sophisticated
- Views: transaxial or axial, coronal, sagittal
- Image volume: basilar tip aneurysm
Two Types of Tomography

‘Tomo’ + ‘graphy’ = Greek: ‘slice’ + ‘picture’

CT: Transmission

PET: Emission
Physics of PET and CT Imaging

The Electromagnetic Spectrum

<table>
<thead>
<tr>
<th>longer wavelength</th>
<th>higher energy</th>
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<tbody>
<tr>
<td>radiofrequency</td>
<td></td>
</tr>
<tr>
<td>microwave</td>
<td></td>
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<tr>
<td>IR</td>
<td></td>
</tr>
<tr>
<td>UV</td>
<td></td>
</tr>
<tr>
<td>X-ray</td>
<td></td>
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<tr>
<td>gamma-ray</td>
<td></td>
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<tr>
<td>cosmic-ray</td>
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AM FM TV

Transmission through 10cm of tissue (i.e. water)

low resolution region (long wavelength)

high resolution region
## Major Medical Imaging Modalities

<table>
<thead>
<tr>
<th>Modality</th>
<th>Resolution (mm)</th>
<th>TX or EM*</th>
<th>Mode</th>
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<tr>
<td>X-ray</td>
<td>0.1 – 1.0</td>
<td>TX</td>
<td>Projection</td>
</tr>
<tr>
<td>Nuclear Medicine</td>
<td>10 – 20</td>
<td>EM</td>
<td>Projection</td>
</tr>
<tr>
<td>X-ray CT</td>
<td>0.5</td>
<td>TX</td>
<td>Tomographic</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>0.3</td>
<td>TX (sound)</td>
<td>Tomographic</td>
</tr>
<tr>
<td>MRI</td>
<td>1</td>
<td>EM (RF)</td>
<td>Tomographic</td>
</tr>
<tr>
<td>SPECT</td>
<td>10</td>
<td>EM</td>
<td>Tomographic</td>
</tr>
<tr>
<td>PET</td>
<td>5</td>
<td>EM</td>
<td>Tomographic</td>
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*(TX = transmission, EM = emission)*
How it works: Positron Emission

Radioactive decay

• decays to stable form by converting a proton to a neutron and ejects a 'positron' to conserve electric charge

• positron annihilates with an electron, releasing two anti-colinear high-energy photons

• detection system is ~1-5% efficient, and can be made quantitative

$E = mc^2$

= 511 keV

$\sim 2$ mm

$\sim 180$ deg
How it works: Scintillation

- A high energy 511 keV photon interacts with the scintillator (e.g. BGO, Dense yet transparent).
- The scintillator emits optical photons (~ 1eV).
- Each UV photon is converted into a current pulse by photomultiplier tubes (PMTs).
- The PMTs have a gain of ~ $10^6$. 

Optical photons (≈ 1eV)

High energy 511 keV photon

Scintillator (e.g. BGO, Dense yet transparent)

Current pulse for each UV photon detected

Gain of ~ $10^6$
PET Detector Block

- PET scanners are assembled in block modules
- Each block uses a limited number of PMTs to decode an array of scintillation crystals

Gammas

Two dual photocathode PMTs

BGO CRYSTALS (6x6)

Reflective light sealing tape

Thin plastic protective sheet

Signal out to processing

Scintillation light
Typical PET Scanner Detector Ring

Face of Crystal Block: 38 mm x 38 mm
Crystal Dimensions: 4.7 mm x 6.3 mm
Depth of Crystals: 30 mm
Detector Ring Diameter: 886.2 mm (crystal to crystal)
Inside GE Discovery STE PET/CT

Block matrix: BGO crystals
- 6 x 8 crystals (axial by transaxial)
- Each crystal:
  - 6.3 mm axial
  - 4.7 mm transaxial

Scanner construction
- Axial:
  - 4 blocks axially = 24 rings
  - 15.7 cm axial extent
- Transaxial:
  - 70 blocks around = 560 crystals
  - 88 cm BGO ring diameter
  - 70 cm patient port
- 13,440 individual crystals
How it works: Timing coincidence

- **Δt < 10 ns?**
- **record positron decay event**
- **reconstruct image of tracer uptake**
Quantitative errors in measurement

- Lost (attenuated) event
- Scattered coincidence event
- Random coincidence event

- Compton scatter
- Incorrectly determined LORs
- No LOR
Effects of Attenuation: Patient Study

- PET: without attenuation correction
  - Reduced mediastinal uptake
  - 'Hot' lungs
  - Non-uniform liver
  - Enhanced skin uptake

- PET: with attenuation correction (accurate)

- CT image (accurate)

Errors in attenuation correction can dominate image quality
• CT images are also used for attenuation correction (CTAC) of the PET data

• Note that images are not really fused, but are displayed as fused or side-by-side with linked cursors
Commercial/Clinical PET/CT Scanner

- rotating CT system
- thermal barrier
- PET detector blocks
How it works: CT Scan Concept

- x-ray tube
- x-ray fan beam
- rotating gantry with tube and detectors attached
- patient
- couch
- detector array
CT Scanner in Operation

64-slice CT, weight ~ 1 ton, speed 0.33 sec (180 rpm)
X-ray CT Tubes

- Rotating anode tube
  (dissipates heat to allow higher beam currents)
# Modern X-Ray Tube

**Electron Collector:** reduce off-focal radiation  
- Lower patient dose

**High Peak-Power Target & Bearings:**  
- High peak-mA for fast rotation

<table>
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<th>Rotation speed (s)</th>
<th>typical mAs</th>
<th>mA needed</th>
</tr>
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<tbody>
<tr>
<td>0.5</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>0.4</td>
<td>200</td>
<td>500</td>
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<tr>
<td>0.35</td>
<td>240</td>
<td>600</td>
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<tr>
<td>0.35</td>
<td>200</td>
<td>571</td>
</tr>
<tr>
<td>0.35</td>
<td>240</td>
<td>686</td>
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### mA needed per kVp (Large Patient)

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<th>kVp</th>
<th>mA Small Spot</th>
<th>mA Large Spot</th>
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<tr>
<td>80</td>
<td>10-300</td>
<td>305-675</td>
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<tr>
<td>100</td>
<td>10-310</td>
<td>315-770</td>
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<tr>
<td>120</td>
<td>10-335</td>
<td>340-800</td>
</tr>
<tr>
<td>140</td>
<td>10-335</td>
<td>340-715</td>
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What are we looking at?
FDG-6-PO₄ is ‘trapped’ and is a marker for glucose metabolic rates.*

Molecular Imaging: Glu Metabolism

[18F]fluorodeoxyglucose (FDG)

![Diagram showing glycolysis and TCA cycle with glucose, glucose 6-phosphate, pyruvate, lactate, TCA (oxidative, efficient), and radioactive fluorine.](image_url)
Imaging FDG uptake (PET) & anatomical localization (CT)

Function

Function+Anatomy and CT-based attenuation correction

Anatomy
# Diagnostic Accuracy of PET/CT exceeds CT or PET only

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\textsuperscript{a}Statistically significant difference when compared with PET/CT. Abbreviations: NSCLC, non-small-cell lung cancer; ND, not determined; TNM, tumor node metastasis.

PET with $^{18}$F-FDG is used for cancer imaging

Currently ~ 92% of all PET/CT studies are for diagnosis and staging in oncology imaging

- About 5000 scanners worldwide
- 2.5 millions scans done annually in US
Response to therapy of liver met gastric GIST

No morphological change in the metastasis

Pre therapy

1 wk imatinib therapy

PET SUV 5 to 1.8

Castell and Cook, British J Cancer 2008
What are the advantages of PET/CT?
Sensitivity

Meikle PMB 2005
Quantitation

What do the image values represent?

Linear with position and tracer concentration
Quantitation

What do the image values represent?

Linear with position and tracer concentration

Linear with position
Improvements and/or Artifacts
Resolution Effects

- Modified NEMA NU-2 Image Quality Phantom (30 cm x 23 cm cross section)
- Sphere diameters: 1.0, 1.3, 1.7, 2.2, 2.8, 3.7 cm
- 4:1 target:background ratio and typical patient activity
- RC = measured / true

![Graph showing Recovery Coefficient (RC) with 2D FBP](image)
Resolution Effects

Resolution and calibration dependent bias

Resolution-dependent broadening

actual value

10 mm

5 mm smoothing

image value (a.u.)

profile

2 cm sphere

5 cm sphere

33 cm
Image Reconstruction: Modeling Detector Blurring

Inter-crystal scattering

- Annihilation photon
- Scintillation (Compton scatter)
- True event crystal
- Light collection

Parallax error

- Assigned event crystal due to scattering
- Crystal thickness
- Assigned line of response (LOR)
- Variable depth of interaction
- True LOR

Shape of detector blurring point spread function (PSF)
- Radially variant
- Asymmetric in transaxial direction
- Two-fold symmetric about FOV center
Spatially-Variant Image Resolution

standard OSEM

OSEM with detector blurring modeled
Including improved physics modeling in image reconstruction

• In principle can remove detector blurring
Phantom measurements: ringing artifact

Bai, 2010 IEEE MIC conf record
Patient shifting

- Large change in attenuation going from spine to lung
Breathing Artifacts: Propagation of CT breathing artifacts via CT-based attenuation correction

Attenuation artifacts from CT can dominate true PET tracer uptake values
Image Smoothing: Noise vs. Resolution

- Always a trade-off in noise vs. resolution
- The choice of the best filter to use with the reconstruction algorithm depends on the clinical task
- There are no standards for choice of smoothing
Effect of changing smoothing

RC for 1 cm spheres:
- 4 mm smoothing: 0.85
- 7 mm smoothing: 0.52
- 10 mm smoothing: 0.40

SNM Chest phantom: True RC is 1.0
Image Quality
Image Quality

Image quality, for the purposes of medical imaging, can be defined as the ability to extract desired information from an image

- Harrison H. Barrett *PNAS, 1993*
Traditional measures: Resolution

- Point-spread function (PSF): Narrower is better
- Modulation transfer function (MTF), which is the absolute value of the frequency-space version of the PSF: Wider is better
- FWHM, FWTM, FW100M, etc - but these can only approximate the PSF
- Bias is related to the PSF, but in a non-trivial way
Traditional measures: Noise

• Sensitivity: response to very low activity levels
• More counts -> lower noise -> Better SNR
• Noise Power Spectrum: noise power at each frequency
• Note that apparent noise in a single image, is not necessarily the same as true noise measured from multiple images.
Law of conservation of difficulty

- There are always trade-offs: In this case usually noise vs. resolution or bias
- Looking at the range of values is important to be fair
- Looking at the operating point may be the most important, but can be difficult to determine
How do you compare images?

- define task
  - detection
  - localization
  - estimation (quantitation)
  - shape discrimination
  - combinations of the above, etc.
- measure (quantitate) task performance
- these are often time consuming studies and can be difficult to perform properly
- we can in some cases use computer models of human performance -- so called ‘model’ or ‘computational’ observers -- that are based on the human perceptual system
Detectability: Is it there?

Noiseless

lesion:background
1 : 1.2 : 1.5 : 2

100 kcounts

10 kcounts

2 kcounts
Decreased resolution

Noiseless

100 kcounts

10 kcounts

2 kcounts
Correlated Noise Introduced by Image Reconstruction

No Noise (reconstructed)

Uncorrelated

Correlated

1M Counts

0.1M Counts
Resolution Effect of Smoothing vs. Noise

Human abdomen simulation with 2cm diam. lesion 2:1 contrast

- More counts (less noise)
- Less smoothing (more noise)
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