SPECT/CT Instrumentation and Clinical Applications

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Educational Objectives:
1. Understand the underlying physical principles of SPECT/CT image acquisition, processing and reconstruction
2. Understand current and future clinical applications of SPECT/CT imaging
3. Familiarization with commercially-available SPECT/CT systems
SPECT/CT Instrumentation and Clinical Applications

• Brief review of SPECT principles
• Iterative SPECT reconstruction
• Advent of SPECT-CT hybrid imaging
• Current clinical applications of SPECT

SPECT Radionuclides

• $^{99m}$Tc $T_{1/2} = 6$ hr, $\gamma = 140$ keV
• $^{111}$In $T_{1/2} = 67$ hr; $\gamma'$s = 172, 245 keV
• $^{123}$I $T_{1/2} = 13$ hr, $\gamma = 159$ keV
• $^{67}$Ga $T_{1/2} = 78$ hr; $\gamma'$s = 93, 184, 296 keV
• $^{201}$TI $T_{1/2} = 73$ hr, 70 keV X-rays, $\gamma = 167$ keV
• $^{131}$I $T_{1/2} = 193$ hr, $\gamma = 364$ keV*
• $^{153}$Sm $T_{1/2} = 46$ hr, $\gamma = 103$ keV*

* employed for internal therapy ($\beta^-$) as well!!!
SPECT Imaging: Inherently 3-D

Acquisition: 2-D projections of a 3-D volume
Reconstruction: contiguous stack of 2-D slices

SPECT Imaging

Radon transform angular symmetry violated

\[ P(\theta) \neq P(\theta + \pi) \]

0° TDC Anterior View  horizontally flipped Posterior
SPECT Imaging

Violates Radon transform symmetry principle:

Differential Attenuation

\[ I(\theta_i) = I_0 e^{-a \int_{\mu(L) dL}} \]

\[ I(\theta_i + \pi) = I_0 e^{-a \int_{\mu(L) dL}} \]

Other Factors

- differential, source-to-detector distance-dependent resolution
- depth-dependent scatter

SPECT Imaging

Projections over 360° instead of 180° (exc. cardiac)
SPECT Imaging

Cardiac SPECT: projections over 180°

θ₁ + 180° - Δθ

Isotropic Pixels and Voxels

Δz = Δr

Δz = Δy = Δx
SPECT Imaging

Isotropic Volume Smoothing
↓ noise amplified by inverse Radon transform ramp filter
2-D filtering of projections ≡ 3-D post-recon filtering
original

2-D Butterworth Filter (0.6 Nyquist, 10th order)

No volume smoothing

Butterworth 0.6 Nyquist, 10th order
\[ I(x,y,\theta_i) = I_0(x,y) e^{-\mu L(x,y,\theta_i)} \]

\[ I_0(x,y) = I(x,y) \times M/\sum_i e^{-\mu L(x,y,\theta_i)} ; i = 1, M \]

Conventional SPECT AC
Chang post-processing algorithm

- assumes constant \( \mu \) value (cm\(^{-1}\))
- requires accurate anatomical boundary definition
- works reasonably well for brain SPECT
- other body sections problematic
  - variable \( \mu \) values (esp. in thorax)
  - accurate boundaries difficult to obtain
Based on ideal Radon inversion formula, which:

- assumes linear, shift-invariant system
- assumes angular symmetry of projections:
  \[ p(r,\theta) = p(-r,\theta+\pi) \]

SPECT imaging system is NOT angularly symmetric nor shift-invariant, with depth-dependent:

- spatial resolution
- attenuation
- scatter

(spatial and energy resolution both play a role)

**Conventional SPECT**

Filtered Backprojection (FBP) Reconstruction

- Backprojection smears information along the entire line of projection (ramp × window filter)
- Doesn’t handle source depth and scatter from it
  - (projections sometimes scatter corrected as a crude “guesstimate”)
- Doesn’t handle variable attenuation (\(\mu(x,y)\))
  - (sometimes approx. w/ constant \(\mu\) and, e.g., Chang)
- Doesn’t handle depth-dependent resolution
  - (frequency-distance principle has been attempted)
Conventional SPECT

FBP Reconstruction Model

\[ p(r, \theta) = \sum f(x, y) \]
along an in-plane line integral

SPECT Imaging

- The intensity in a voxel \( b \) \( (n(b)) \), is Poisson:

\[ P(n(b)) = P(n \mid \lambda(b)) = e^{-\lambda(b)} \frac{\lambda(b)^n}{n!} \]

- as is that in detector \( d \) \( (y(d)) \):

\[ P(y(d)) = P(y \mid \lambda(d)) = e^{-\lambda(d)} \frac{\lambda(d)^y}{y!} \]

- The probability that a photon emitted from voxel \( b \) is detected by detector \( d \) is \( p(b, d) \)
SPECT Imaging

True detector intensity = sum of true voxel intensities weighted by detection probabilities

\[
\lambda(d) = \sum_{b=1}^{B} \lambda(b) p(b, d)
\]

Let \(x(b,d)\) = # of emissions from \(b\) measured in \(d\)

Many possible sets \(x(b,d)\) → the measured \(y(d)\)

\(x(b,d)\) is Poisson with intensity

\[
\lambda(b, d) = \lambda(b) p(b, d)
\]
SPECT Imaging
Iterative Reconstruction

- Reconstruction based upon the Poisson statistical nature of SPECT imaging (measurement of radioactive decay)
- Can incorporate modeling of the physics of SPECT imaging
  - System (intrinsic + collimator) spatial resolution
  - Attenuation by the patient
  - Compton Scatter (in patient, collimator, crystal)
  - Collimator septal penetration
  - Energy resolution (future)

SPECT Imaging
Iterative Reconstruction Methods

- ART (algebraic reconstruction technique)
- MART (multiplicative ART)
- WLS-CG (weighted least-squares conjugate gradient)
- **EM (expectation maximization)!!!**
  - ML (maximum likelihood)
  - MAP (maximum a posteriori)
- **OS (ordered subset)!!!**
SPECT Imaging
OS-EM Reconstruction

• >> ↑ rate of convergence using an ordered subset of all projections at a time
• A series of “mini-EMs” performed until all projections have been cycled through per iteration
• m OS-EM iterations with n subsets ≅ m × n ML-EM iterations
• OS-EM parameters specified:
  - # of subsets (n) and # of iterations (m)

Expectation Maximization

• Estimates parameters of the statistical distributions underlying the measured data
• In the case of SPECT
  - λ of the Poisson distribution for each voxel
  - given the measured projection data
  - λ represents the true count rate in each voxel
Conditional Expectation

\( k+1 \)th estimate of \( x(b,d) \)

\[
x^{[k+1]}(b, d) = E[x(b, d) \mid y, \lambda^{[k]}] = E[x(b, d) \mid y(d), \lambda^{[k]}]
\]

\[
x^{[k+1]}(b, d) = \frac{y(d)\lambda^{[k]}(b, d)}{\sum_{b' = 1}^{B} \lambda^{[k]}(b', d)}
\]

\[
x^{[k+1]}(b, d) = \frac{y(d)\lambda^{[k]}(b) p(b, d)}{\sum_{b' = 1}^{B} \lambda^{[k]}(b') p(b', d)}
\]

Maximum Likelihood

• Find the parameter \( \lambda \) that makes the measured outcome most likely.

\[
\max_{\lambda} p(x \mid \lambda) = \frac{\lambda^x e^{-\lambda}}{x!}
\]

• The maximum likelihood estimator of \( \lambda \) is the measured quantity \( x \).
To maximize with respect to $\lambda(b)$,

$$0 = \frac{\partial}{\partial \lambda(b)} L_y(\lambda) \rightarrow - \sum_{d \in 1...D} p(b,d) + \sum_{d \in 1...D} \frac{y(d) \lambda(b,d)}{\lambda(b^*,d)}$$

$$\lambda(b) \sum_{d \in 1...D} p(b,d) = \sum_{d \in 1...D} \frac{y(d) \lambda(b,d)}{\lambda(b^*,d)}$$

$$\frac{\lambda^{[k+1]}(b,d)}{\sum_{j=1}^N p(b,d)} = \frac{\sum_{j=1}^N x^{[k+1]}(b,d)}{\sum_{j=1}^N p(b,d)}$$

**ML-EM**

Choose an initial parameter $\lambda^{[0]}$. Set $k=0$.

1st estimate = uniform cylinder or FBP

Estimate the number of counts in each pixel of the projections that came from each voxel of the volume.

$$x^{[k+1]}(b,d) = \frac{y(d) \lambda^{[k]}(b,d)}{\sum_{b'} \lambda^{[k]}(b',d)}$$

$$\lambda^{[k]}(b,d) = \lambda^{[k]}(b) p(b,d)$$

Choose the next estimate of $\lambda$ so that it makes the estimated data above most likely.

$$\lambda^{[k+1]}(b) = \frac{\sum_{d=1}^D x^{[k+1]}(b,d)}{\sum_{d=1}^D p(b,d)}$$
ML-EM: One Iteration

\[ \lambda^{[k+1]}(b) = \frac{\lambda^{[k]}(b) \sum_{d=1}^{D} y(d) p(b, d)}{\sum_{d=1}^{B} \sum_{b'=1}^{B} \lambda^{[k]}(b') p(b', d)} \]

The Key to ML-EM

- The probability (or system) matrix in

\[ \lambda^{[k+1]}(b) = \frac{\sum_{d=1}^{D} \lambda^{[k]}(b, d)}{\sum_{d=1}^{D} p(b, d)} \]

- \( p(b, d) \) captures the probability that a count in a particular voxel of the volume will wind up in a particular pixel in a particular projection.
p(b,d) Can Capture:

1. Depth-dependent resolution
2. Position-dependent scatter in the patient
3. Depth-dependent attenuation

We can thus use a measured attenuation map along with models of scatter and camera resolution to perform a far more accurate reconstruction.

Warning, though: GIGO principle applies!!!
SPECT Iterative Reconstruction
Noise Reduction (Smoothing)

1. Pre-filtering of original projections
2. Regularization: Maximum A-Priori (MAP) EM algorithms
   • prior knowledge (e.g., anatomical)
   • smoothness criteria
3. Post-filtering of reconstructed volume, e.g., Gaussian (filter FWHM specified)

SPECT Iterative Reconstruction
MAP-EM Example
Median Root Prior (MRP) Penalized-Likelihood

\[ \lambda^{[k+1]}(b) = \frac{\sum_{d=1}^{D} y(d) p(b, d)}{\sum_{d=1}^{D} p(b, d)} + \beta \left[ \frac{\lambda^{[k]}(b) - M(b)}{M(b)} \right] \]

\[ M(b) \text{ obtained from median filter of image of } \lambda^{[k]}(b) \]
\[ \beta = \text{ unit-less control parameter} \]
SPECT Iterative Reconstruction
Attenuation Modeling

\[ p(r, \theta) = \sum f(x, y) \times p_{\text{att}}(x, y, r, \theta) \]
along a line integral
\[ p_{\text{att}}(x, y, r, \theta) = \text{probability due to attenuation} \]
\[ p_{\text{att}}(x, y, r, \theta) = \exp(-\sum_{ab} \mu(x', y') \Delta(x', y')) \]

CT-Based Attenuation Map
(\(\mu\ map\))
Can account for variably attenuating media
SPECT Iterative Reconstruction
Attenuation Modeling

99mTc SestaMIBI (Parathyroid adenoma)

System Resolution ($R_s$) Modeling
Distance-dependent collimator beam

$R_s = \sqrt{R_i^2 + R_c^2}$

Intrinsic Detector Resolution $R_i$
Collimator Resolution $R_c$ a linear function vs $r$
Pencil Beam (FBP)
Fan Beam (2D iterative)
Cone Beam (3D iterative)
SPECT Iterative Reconstruction
System Resolution Modeling

2D: \( p(r,\theta) = \sum f(x,y) \times p_{\text{res}}(x,y,r,\theta) \)
3D: \( p(r,\theta) = \sum f(x,y,z) \times p_{\text{res}}(x,y,z,r,\theta) \)

\( p_{\text{res}} \) = probability due to resolution
“fan of acceptance” (2D fan beam model)
“cone of acceptance” (3D cone beam model)

SPECT Iterative Reconstruction
System Resolution Modeling
Collimator-Detector Response Function (CDRF)

Intrinsic Response (IRF)
Geometric Response (GRF)
Septal Penetration Response (SPRF)
Septal Scatter Response (SSRF)
SPECT Iterative Reconstruction
System Resolution Modeling
Collimator-Detector Response Function (CDRF)

Depends upon:

- Radionuclide Gamma Emissions/Energies, e.g.,
  - Tc-99m (140 keV)
  - I-131 (364 keV + 637, 723 keV)

- Energy Window(s), e.g.,
  - I-131 (364 keV/15%)
  - In-111 (174 keV/15%, 245/15%)

- Collimator Parameters
  - hole shape/diameter/length (geometric response)
  - septal thickness (septal penetration/septal scatter)

SPECT Iterative Reconstruction
System Resolution Modeling

\[ \text{Standard Filtered Backprojection} \]
\[ \text{2-D OSEM w/ fan beam modeling (m=12,n=10)} \]
\[ \text{3-D OSEM w/ cone beam modeling (m=25,n=10)} \]

\[ \text{99mTc Bone Scan, Low-Energy High-Resolution Collimator} \]

- 2-D pre-filter: Butterworth, \( f_c = 0.6 \) Nyquist, order = 10
- 3-D Gaussian Post-Filter (7.8 mm FWHM)
SPECT Iterative Reconstruction

System Resolution Modeling

\[ \text{\^{67}Ga Citrate, Medium-Energy Low-Penetration Collimator} \]

- FBP
- 2-D OSEM w/ fan beam modeling (m=12, n=10)
- 3-D OSEM w/ cone beam modeling (m=25, n=10)

\[ \begin{align*}
\text{p}(r, \theta) &= \sum f(x,y) \times p_{\text{res}}(x,y,r,\theta) \times p_{\text{attn}}(x,y,r,\theta) \\
\text{p}(r, \theta) &= \sum f(x,y,z) \times p_{\text{res}}(x,y,z,r,\theta) \times p_{\text{attn}}(x,y,z,r,\theta)
\end{align*} \]
SPECT Imaging: Compton Scatter

- Reduces contrast
  - low frequency blur to the image
- Depends on
  - photon energy
  - camera energy resolution, window setting
  - object shapes, $p$'s, radionuclide distributions
- Compensation must occur before attenuation
  - attenuation assumes complete removal of attenuated photons from the "beam"
  - in SPECT imaging, "beam" contains scatter

SPECT Iterative Reconstruction

DEW/TEW Scatter Pre-Correction

- For each photopeak projection image, $P(x,y,\theta)$, estimate scatter as a weighted sum of one (dual-energy-window) or two (triple-energy-window) adjacent scatter window images, $C_i(x,y,\theta)$.

- Subtract scatter prior to reconstruction:

$$S(x,y,\theta) = \sum_i k_i \times C_i(x,y,\theta)$$

$$P_{corr}(x,y,\theta) \rightarrow P(x,y,\theta) - S(x,y,\theta)$$

$k_i = \text{scatter window image } i \text{ weighting factor}$
SPECT Iterative Reconstruction
I-131 TEW Scatter Pre-Correction

\[
P(x,y,\theta) = P_1(x,y,\theta) (LS) + P_2(x,y,\theta) (US) - P_{cor}(x,y,\theta)
\]

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Part} & \text{Center (keV)} & \text{Width} (%) & \text{Shift} (%) & \text{Type} \tabularnewline \hline
38k & 15 & 0 & \text{Photopeak} & \text{Photopeak} \tabularnewline
15 & & & \text{Lower Scatter} & A1 \tabularnewline
15 & & & \text{Upper Scatter} & A1 \tabularnewline \hline
\end{array}
\]
SPECT Iterative Reconstruction
DEW/TEW Iterative Scatter Modeling

• Estimate scatter contribution to each photopeak projection pixel \( d \), \( S(d) \), as a weighted sum of counts, \( C_i(d) \), from one (DEW) or two (TEW) adjacent scatter windows.

• Incorporate into the forward projection step:

\[
P_{\text{est}}'(d) \rightarrow P_{\text{est}}(d) + S(d)
\]

\[
S(d) = \sum k_i \times C_i(d)
\]
SPECT Iterative Reconstruction
DEW/TEW Iterative Scatter Modeling

\[
\lambda^{[k+1]}(b) = \frac{\sum_{d=1}^{D} y(d) p(b, d)}{\sum_{d=1}^{D} p(b, d)} \left[ \lambda^{[k+1]}(b') p(b', d') + S(d) \right]
\]

scatter contribution to detector \(y(d)\) incorporated into forward projector

Effective Scatter Source Estimation

Current Recon Estimate \(\times\) Scatter Kernel \(\times\)

Next Projection Scatter Estimate \(S(d)\)

Forward Project w/ Attenuation

\(\rho\) Map

\(\mu\) Map

ESS
SPECT Iterative Reconstruction

Scatter Modeling in the System Matrix $p(b,d)$

$$p(b,d) = p_S(b) \times p_S(b,d) \times p_A(b,d) \times p_D \times p_E$$

- $p_S(b) = \text{prob. of scatter}$
- $p_S(b,d) = \text{prob. of scatter into det. } d$
- $p_A(b,d) = \text{prob. due to attenuation}$
- $p_D = \text{prob. due to det. efficiency}$
- $p_E = \text{prob. due to energy resolution}$

SPECT/CT Imaging: Why?

- **SPECT Attenuation Correction**
  - Quantitative SPECT ≡ NM’s “holy grail”
    - requires attenuation artifact removal for
    - absolute quantification of uptake in 3-D (like PET)
      (accurate scatter correction also needed)
  - Previous AC methods have not worked well
    - constant $\mu$ pre-/post-processing (e.g., Sorenson, Chang)
    - radioactive source-based transmission CT attachments
- **Improved Localization**
  - Functional-anatomical overlay (image fusion)
    - requires registered dual-modality data

(Future: CT = scatter modeling media)
SPECT/CT Image Registration

Methods:
- Manual
  w/o or w/ fiducials
- Semi-automated
  - fiducials
  - anat. landmarks
- Automated
  - AIR
  - Mutual Info.

SPECT/CT Imaging: Software

Registered CT Image-Based SPECT $\mu$ Map

Parameters:
- HU-to-cm$^{-1}$ function
  - piece-wise bilinear
    (most common)
- Effective keV
  - CT (~ 70 – 80)
  - SPECT (nuclide dep.)
- Attenuation beam model
  - narrow
  - broad
    (w/o scatter correction)
- $\mu$ map image smoothing

But what if CT and SPECT beds are not identical? Uh-oh! GIGO!
CT-Based SPECT μ Values

Material attenuation versus Energy

- Air
- Muscle
- Bone

CT

μ/ρ (cm/g)

Energy (keV)

CT: 75 (effective)
SPECT: 140 (99mTc)

Transform

[μ_{75}(H_2O) μ_{75}(m)] / [μ_{140}(H_2O) μ_{140}(m)]

Material m

1.22 (HU ≤ 0)
1.43 (HU > 0)

Example CT HU-to-SPECT cm⁻¹ transform

(standard: piece-wise bilinear function)
SPECT/CT Imaging: Software

Iterative Reconstruction

- FBP w/ Butterworth 0.4/5
- 3-D OSEM w/ resolution modeling
- 3-D OSEM w/ resolution and attenuation modeling

Original “SPECT/CT” scanners

Gd-153 (100 keV γ) source “transmission CT”

Limitations

1. Poor resolution/partial volume (esp. air, lung, soft tissue, bone interfaces)
2. Poor statistics (noisy images, heavy smoothing)
3. Dead-time (imaged with gamma camera detector)
4. Emission Contamination (e.g., Tc-99m downscatter)
5. Designed for cardiac

Supplanted by SPECT/X-ray CT
SPECT/CT Imaging: Hardware
Hawkeye® (GE Healthcare)

Hawkeye®
(Original 1-slice CT)

Infinia / VC Hawkeye-4
(Current 4-slice CT)

Slide courtesy of Osnat Zak, GE Healthcare

SPECT/CT Imaging: Hardware

Advancements in SPECT/CT
Infinia Hawkeye-4

Slide Courtesy of Osnat Zak, GE Healthcare
SPECT/CT Imaging: Hardware

Hawkeye-4 CT (GE Healthcare)

Design Considerations
• Low radiation dose
• Time Averaged CT
• Accurate SPECT-CT alignment
• Integration & Workflow
• Same gantry and footprint

mA: 1.0 – 2.5
kVp: 140 (default), 120
Collimation: 4 × 5 mm
Slice Thickness: 5 mm (axial)
Acq. Time (axial): 15 sec/20 mm (180° + fan) or 5 min/40 cm
FOV: 45 cm (512 × 512 = 0.88 × 0.88 pixels)
Patient Port: 60 cm

Dose Comparison (40 cm)

<table>
<thead>
<tr>
<th>X-ray tube voltage</th>
<th>Hawkeye4</th>
<th>Hawkeye4</th>
<th>Conventional CT</th>
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<tbody>
<tr>
<td>Tube current</td>
<td>1mA</td>
<td>2.5mA</td>
<td>20-80 mA</td>
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<tr>
<td>Patient dose</td>
<td>0.72 mSv</td>
<td>1.8 mSv</td>
<td>&gt;6.5 mSv</td>
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</table>

Slide Courtesy of Osnat Zak, GE Healthcare

SPECT/CT Imaging: Hardware

GE Hawkeye

Bone WB  | x 1 SPECT View  | 40cm CT AC + Anatomy |
15 min   | 20 min          | 10 min               |
45 Minutes

GE Hawkeye-4 Evolution for Bone

Bone WB  | x 1 SPECT Views | 40cm CT AC + Anatomy |
15 min   | 10 min          | 5 min                |
30 Minutes

GE Hawkeye-4 Evolution for Bone

x 3 SPECT Views  | 80 cm CT AC + Anatomy |
30 min           | 10 min              |
40 Minutes

Evolution
Iterative Recon
includes
Collimator-Detector
Response

Slide Courtesy of Osnat Zak, GE Healthcare
SPECT/CT Imaging: Hardware
Philips Healthcare

Precedence 6 & 16

BrightView XCT (New)

Slide Courtesy of Ling Shao, Philips Healthcare

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SPECT/CT Imaging: Hardware
Precedence (Philips Healthcare)

- kVp: 90, 120 or 140
- mA: 20 – 500
- FOV: 50 cm (512 × 512 = 0.98 × 0.98 pixels) up to 150 cm (axial)
- Collimation:
  - 6-slice: 2 × 0.6, 6 × 0.75, 6 × 1.5, 6 × 3, 4 × 4.5, 4 × 6.0 mm
  - 16-slice: 2 × 0.6, 16 × 0.75, 16 × 1.5, 8 × 3, 4 × 4.5 mm
- Slice Thickness: 0.65 – 7.5 mm (spiral), 0.6 - 12 mm (axial)
- Scan Speed (spiral)
  - 0.4, 0.5, 0.75, 1, 1.5, 2 sec/360°; 0.28, 0.33 sec/240°
- Patient Port: 70 cm
- Resolution: 24 lp/cm
- Dose (CTDI): 12.85 mGy/100 mAs (head), 6.5 mGy/100 mAs (body)
- Registration error ≤ 4mm (one pixel)

Slide Courtesy of Ling Shao, Philips Healthcare
SPECT/CT Imaging: Hardware

BrightView XCT (Philips Healthcare)

- Flat Panel Volume CT technology
- Coplanar with SPECT Imaging (cardiac -14 cm)
- Localization, CT-AC, Bone Imaging
- Max. Rotation Speed: 12 sec for 360° (14 cm axial FOV)
- Slice thickness: 0.33 – 2.0+ mm (isotropic voxel)
- Resolution: >15 lp/cm
- Dose (CTDI) - Typical:
  - ~6 mGy (body localization)
  - ~1 mGy (AC)
- Registration error: ≤ 4mm (one pixel)

Volumetric CT components:
- Rotating anode X-ray tube
- 120 kVp X-ray generator
  - pulsed or continuous
- 4030CB flat panel detector
  - 10, 30, 60 fps, dynamic gain
- X-ray collimator and beam shaper
- CBCT image recon using GPU

Volumetric CT system goals:
- X-ray cone-beam overlaps SPECT FOV
- 360° Gantry rotation within a breath-hold
- Low-dose CT acq. parameters
- Integrated hybrid software solution

Slide Courtesy of Ling Shao, Philips Healthcare
SPECT/CT Imaging: Reconstruction
Astonish (Philips Healthcare)

- 3D Astonish OSEM Reconstruction
  - Resolution, attenuation and scatter corrections
  - Multiple-peak isotope
  - > 5 mm SPECT reconstruction resolution
- Half-time Acquisition
  - Equal or better image quality with Astonish
- Typical SPECT/CT acquisition
  - Bone scan
    - 15 min SPECT + 2 min CT → 7 min + 2 min
  - Cardiac scan
    - 15 min SPECT + 2 min CT → 7 min + 2 min

Slide Courtesy of Ling Shao, Philips Healthcare

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SPECT/CT Imaging: Hardware
Symbia® T (Siemens Medical Solutions USA)

1-, 2-, 6- or 16-slice CT
**SPECT/CT Imaging: Hardware**

*Symbia® T (Siemens Medical Solutions USA)*

**Scalable/Upgradeable**

<table>
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<th>Collimation (mm)</th>
<th>T</th>
<th>T2</th>
<th>T6</th>
<th>T16</th>
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<td>6×0.5 to 6×3</td>
<td>16×0.6 to 16×1.2</td>
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<td>0.6 s</td>
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<th>T2</th>
<th>T6</th>
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<td>2</td>
<td>6</td>
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<th>T</th>
<th>T2</th>
<th>T6</th>
<th>T16</th>
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<th>T2</th>
<th>T6</th>
<th>T16</th>
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<td>20 - 345</td>
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<th>Slice width (mm)</th>
<th>T</th>
<th>T2</th>
<th>T6</th>
<th>T16</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, 5, 8</td>
<td>1 - 10</td>
<td>0.63 - 10</td>
<td>0.6 - 10</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>FOV (cm)</th>
<th>T</th>
<th>T2</th>
<th>T6</th>
<th>T16</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 (512 × 512 = 0.98 × 0.98 pixels) up to 200 (axial)</td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Patient Port</th>
<th>T</th>
<th>T2</th>
<th>T6</th>
<th>T16</th>
</tr>
</thead>
<tbody>
<tr>
<td>70 cm</td>
<td></td>
<td></td>
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</tbody>
</table>

*CARE Dose 4D AEC+DOM dynamic dose reduction algorithm (~8 – 12 mGy CTDiVol @ 130 kVp/90 ref. mA)*
SPECT/CT Imaging: Reconstruction
Flash3D (Siemens Medical Solutions USA)

- Flash3D OSEM Reconstruction
  - 3D collimator resolution compensation
    - in both forward and back-projection directions
    - 3D Gaussian PSF v. distance from collimator
  - Attenuation compensation (CT-based AC maps)
  - Scatter compensation
    - DEW/TEW-based scatter projection images
    - Additive in forward projection
- Multiple-peak isotopes
  - Each photopeak reconstructed separately
  - AC maps and scatter images for each peak
  - Post-summation of peak reconstructions
SPECT/CT Imaging: AC Map

Multi-$\gamma$ Radionuclide (GE Hawkeye 1-Slice)

$\mu$(material($x,y,z$), $\gamma_{high}$) computed ($^{67}$Ga $\gamma_{high}$ = 296 keV)

$\alpha_{low} = \mu(H_2O_{low}) / \mu(H_2O_{high})$

$^{67}$Ga: $\alpha_{93keV} = 1.476$, $\alpha_{184keV} = 1.197$

$AF = e^{-\int L(\theta) dL(\theta)}$

$AF(x,y,\theta)_{multi} = \sum W_{y_i} \times AF_{y_i}$ (Where $W_{y_i}$ = rel. Wt. of $y_i$)

($^{67}$Ga: $W_{93} = .54$, $W_{184} = .295$, $W_{296} = .165$ [measured])

(Note: bone attenuation will be underestimated)

---

SPECT/CT Imaging: AC Map

Multi-$\gamma$ Radionuclide (Siemens Symbia T)

$^{111}$In

172 keV photopeak

247 keV photopeak

172 keV lower scatter

172 keV upper scatter

247 keV lower scatter
SPECT/CT Imaging: AC Map
Multi-\(\gamma\) Radionuclide (Siemens Symbia T)

\(\text{\(^{111}\)In 172 keV photopeak}\)
\(\text{\(^{111}\)In 247 keV photopeak}\)

SPECT/CT Imaging: Hardware
NM-CT FOV Calibration

1. SPECT/CT = SPECT and CT scanning with a common patient handling system (bed)
2. Scanners are mechanically aligned (± tolerance)
3. Same anatomical slice must be aligned SPECT↔CT
4. Minor adjustment needed to correct for residual alignment errors between the two FOVs
   • Transformation: \(\Delta x, \Delta y, \Delta z, \Delta \alpha, \Delta \beta, \Delta \gamma\)
5. Calibration for each set of collimators and detector configuration (180° and 90°) may be required
SPECT/CT Imaging: Hardware

NM-CT FOV Calibration: GE Hawkeye

- Automatically Detects the landmarks
- Calculates the offsets in X, Y, Z and θ
- Applies the offsets to SPECT-CT scans

Alignment Phantom containing 6 landmarks (m\(^{99}\)Tc solution in standard syringes) is scanned by both SPECT and CT

Slide Courtesy of Osnat Zak, GE Healthcare

---

SPECT/CT Imaging: Hardware

NM-CT FOV Calibration: Siemens Symbia

- 10 point sources
- Spiked with:
  - CT contrast material
  - Tc-99m activity

SPECT-CT acquisition/reconstruction of sources placed in plastic holders performed

Cotton swab tip in plastic vial
SPECT/CT Imaging: Hardware
NM-CT FOV Calibration: Siemens Symbia

Iteratively solve for transformation matrix
SPECT/CT Imaging: Hardware
Example NM-CT FOV Registration Test

ACR SPECT phantom

50 μCi Co-57 button sources
(~10 μCi eff. in Tc-99m energy window)

SPECT/CT Imaging: Hardware
Example NM-CT FOV Registration Test
SPECT/CT Imaging: Hardware

Example NM-CT FOV Registration Test

CT μ map artifacts:
everything BUT contrast and motion
CT $\mu$ map artifacts
CT contrast material

4 hr $^{111}$In Octreo $\mu$ map
24 hr $^{111}$In Octreo $\mu$ map

4 hr $^{111}$In Octreotide
24 hr $^{111}$In Octreotide

Activity created!!!
Contemporaneous, NOT simultaneous, SPECT and CT scans!!!

Thus, there can be patient motion between the two scans!!!

SPECT/CT: Motion Correction

SestaMIBI Parathyroid adenoma
Clinical SPECT/CT

- Attenuation Correction
  - General NM
  - Cardiac
- Tumor Localization
  - Anatomical overlay on functional image
- Improved Diagnostic Accuracy (bi-directional)
  - CT: Density, Morphology, Structure (e.g., skeletal)
  - SPECT: Physiology
  - Additional anatomical information added to SPECT
  - Additional physiological information added to CT

SPECT Applications (numerous)

- Stress/Rest Myocardial Perfusion Imaging of CAD
  - Stress: $^{99mTc}$-sestaMIBI or $^{99mTc}$-Tetrafosmin
  - Rest: $^{99mTc}$-labeled agents or $^{201Tl}$ chloride
- $^{99mTc}$-MDP: bone diseases, cancer metastatic to bone
- $^{111In}$-Octreotide: neuroendocrine cancers
- $^{123I}$-MIBG: pheochromocytoma, neuroblastoma
- $^{99mTc}$-sestaMIBI: parathyroid adenomas
- $^{67Ga}$-Citrate: inflammation, lymphoma
- $^{111In}$-ProstaScint: prostate cancer
- $^{131I}$-Nal: thyroid cancer (diagnosis, dosimetry, treatment planning)
- $^{99mTc}$-sulfur colloid: lymphoscintigraphy, liver/spleen
- $^{99mTc}$-red blood cells: hemangioma
- $^{99mTc}$-HMPAO, -ECD: brain perfusion
- $^{201Tl}$ chloride: tumor perfusion (e.g., brain)
- $^{111In}$-Zevalin, $^{153Sm}$-EDTMP: dosimetry, treatment planning
88 YOM, referred for a bone scintigraphy due to severe back pain. On a regular X-ray, a fracture was detected at T11, raising the differential diagnosis between an old and a recent fracture.

On SPECT-CT bone scintigraphy, increased uptake was detected at T11 including the anterior and posterior vertebral elements compatible with a recent fracture.

Tc-99m Bone SPECT/CT (Hawkeye)

- 202 lbs (92 kg), Male, 25 yrs, Dx: Right knee sarcoma. One 24-s CT
- SPECT parameters:
  - 120 kVp/80 mA
  - 10 ms pulse, 14.9 mGy
  - 25.3 mCi Tc-99m MDP, 3 hrs p.i.
- CT resampling:
  - 128 x 128, 128 views, 20 s, 1.4 zoom
  - 0.64 mm voxels
WB Bone SPECT/CT: CT First (Symbia)

- Top of head-to-mid thigh
- 36.4 cm axial FOV per bed
- CT scan length set to 109.2 cm (36.4 cm x 3)
- CT scan FOV adjusted axially
- Max. CT recon FOV (50 cm)
- 2.5 mm thick/2 mm increment
- Followed by 3-bed SPECT over same axial FOV

Whole Body Bone SPECT Acquisition

- NCO Continuous Acquisition
- 180 views x 5 sec/view
- 7.5 min total acquisition time/bed
- 3 beds: 25 min
- 4 beds: 34 min
- Recon: 15 ss/8 iters 8 mm filter
**Tc-99m SestaMIBI (Symbia)**

Parathyroid Adenoma – Surgery Planning

1.25 mm thick/1.0 mm increment 25 cm FOV CT recon for improved pre-surgical localization

Parathyroid adenoma localized with SPECT/CT

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**In-111 Octreotide (Hawkeye)**

Neuroendocrine tumor localization

*Images Courtesy of Mark Madsen, Dept of Radiology, U. of Iowa MC*
Tc-99m SC Lymphoscintigraphy
Sentinel Lymph Node – Pre-Surgical Localization

Melanoma in the left upper back

Tc-99m WBC (Hawkeye)

Malignant lymphoma

• Clinical History:
  • Man aged 22. Lower back pain and decreased general condition.

• Findings:
  • White blood cell scintigraphy: SPECT shows medullary destruction at level of D12, L2, S1 and the left iliac bone.
  • Hawkeye CT shows heterogeneous bone structure, Paget-like, in the concerned areas although malignant bone formation can't be excluded. FDG-PET and bone scintigraphy are positive.

• Diagnosis:
  • Aggressive Non Hodgkin Lymphoma.

Images Courtesy of Clinic St Jean, Brussels, Belgium

Slide Courtesy of Osnat Zak, GE Healthcare
In-111 ProstaScint (Symbia)

96-hour SPECT/CT

Suspicious finding on SPECT = metastatic node on SPECT/CT

I-131 Nal (Hawkeye)

96 hours post-therapy

Skeletal Mets
Cardiac SPECT/CT (BrightView)

- 194 lbs (88 kg), Male, 49 yrs, Dx: Pre-op clearance, Abnormal EKG
- 60-second CT, tidal breathing and 12-second CT, end expiration BH

<table>
<thead>
<tr>
<th>CT parameters:</th>
<th>SPECT parameters:</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 second</td>
<td></td>
</tr>
<tr>
<td>120 kVp/5 Ma</td>
<td>12 second</td>
</tr>
<tr>
<td>10 msec pulse width</td>
<td>120 kVp/2.5 mA</td>
</tr>
<tr>
<td>1.2 mGy CTDI_{VOL}</td>
<td>continuous</td>
</tr>
<tr>
<td></td>
<td>0.79 mGy CTDI_{VOL}</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>120 kVp/2.5 mA</td>
<td>Persantine stress, 2.5 hrs p.i.</td>
</tr>
<tr>
<td>continuous</td>
<td>35 mCi Tc-99m MIBI</td>
</tr>
<tr>
<td>64 x 64, 64 azimuths</td>
<td>20 sec/azimuth, 1.46 zoom</td>
</tr>
</tbody>
</table>

Images courtesy of Radiological Associates of Sacramento

Slide Courtesy of Ling Shao, Philips Healthcare

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Cardiac SPECT/CT (Symbia)
Y-90 Microspheres SIRT (Symbia)

- Tc-99m MAA Liver Catheter Placement (Future: Dosimetry)
- Y-90 SIR-Spheres Liver 24-h Bremsstrahlung (80 keV/30%) (Post-Therapy Confirmation)

Tc-99m MAA Perfusion (Symbia)

Lung Function-Based IMRT Treatment Planning

- Perfusion SPECT
- Percentile Perfusion Image
- Green = 50th percentile contour (top 50% of pixels)
- Orange = 90th percentile contour (top 10% of pixels)
Tc-99m MAA Perfusion (Symbia)
Lung Function-Based IMRT Treatment Planning


Sm-153 EDTMP (Symbia)
Skeletal Tumor Dosimetry

• High-Dose Sm-153 EDTMP Skeletal Targeted Therapy
• 30 mCi/kg (1935 mCi total)
• Target absorbed dose in L shoulder tumor ≥ 40 Gy
• Dose to bladder and kidneys < 20 Gy (planar estimates)
• Dosimetric imaging (30 mCi Sm-153 tracer dose)
  • Whole body planar images (0, 2, 4, 23, 28, 47, 51 h)
  • SPECT/CT of L shoulder tumor at 24 h
• Volume and activity @ 24 h in, tumor estimated by quantitative SPECT
Sm-153 SPECT Scatter Modeling

Energy Spectrum of Sm-153

- TEW Scatter Est.

Sm-153 EDTMP Planar Imaging

L Shoulder Tumor Activity (cts) vs. Time

Geometric Mean of Net Counts

$$\sqrt{C_{\text{Ant}} \times C_{\text{Post}}}$$

tumor
Sm-153 Quantitative SPECT
Tumor Volumetric Analysis

SPECT Tumor Estimates
(6% threshold)
Volume (683 cc)
Counts @ 24 h

Sm-153 SPECT/CT
Sensitivity Calibration (Cts/uCi)

Standard: ~1 mCi in 10 ml
(in abdominal scatter phantom)

\[ Cts/uCi = \frac{C_{std}}{A_{std}} \]

\[ C_{std} = \text{SPECT Cts in std VOI} \] (30% threshold)
\[ A_{std} = \text{uCi in std} \]
\[ S = \frac{C_{std}}{A_{std}} \]
Sm-153 EDTMP SPECT/CT

Tumor absolute activity (FIA) versus Time

\[ \text{FIA}_{\text{bio}}(t) = 0.15 \left(1 - e^{-0.693t/0.5h}\right) \]

Effective FIA(t) = FIAbio(t) e^{-0.693t/46.3h}, T = AUC (integral)

\[ \text{FIAbio}(t) = 0.15 \left(1 - e^{-0.693t/0.5h}\right) \]

Sm-153 EDTMP SPECT/CT

Skeletal Tumor Dose Estimate

Tumor (Electron) Dose Estimate

Mass (M) = 0.683 kg (1 g/cc)

Mean e⁻ energy per decay (E) = 0.153 Gy-kg/GBq-h

\[ A \text{ (GBq)} = 71.6 \]

Residence Time (T) = 10.7 h

Dose \( (E \times A \times T / M) = 172 \text{ Gy} \)
References


