SPECT/CT Instrumentation and Clinical Applications

William Erwin, M.S.
The University of Texas
M. D. Anderson Cancer Center
Houston, TX

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SPECT/CT Instrumentation and Clinical Applications

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

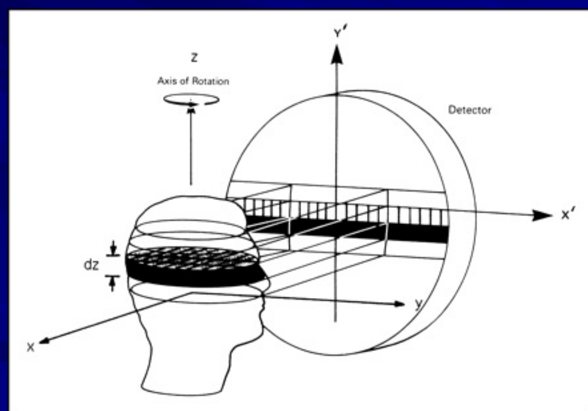
- ^{99m}Tc $T_{1/2}$ = 6 hr, γ = 140 keV
- ^{111}In $T_{1/2}$ = 67 hr; γ's = 172, 245 keV
- ^{123}I $T_{1/2}$ = 13 hr, γ = 159 keV
- ^{67}Ga $T_{1/2}$ = 78 hr; γ's = 93, 184, 296 keV
- ^{201}Tl $T_{1/2}$ = 73 hr, 70 keV X-rays, γ = 167 keV
- ^{131}I $T_{1/2}$ = 193 hr, γ = 364 keV*
- ^{153}Sm $T_{1/2}$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

* employed for internal therapy (β^-) 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

$P(\theta) \neq P(\theta+\pi)$

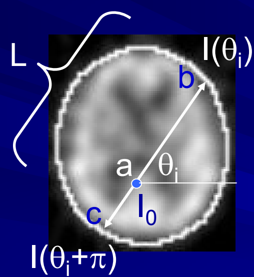
0° TDC Anterior View

horizontally flipped Posterior

SPECT Imaging

Violates Radon transform symmetry principle:

Differential Attenuation



$$I(\theta_i) = I_0\, e^{-\int_a^b \mu(L)dL}$$

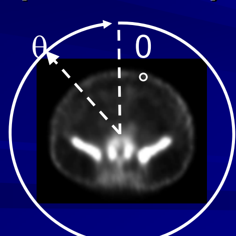
$$I(\theta_i+\pi) = I_0\, e^{-\int_a^c \mu(L)dL}$$

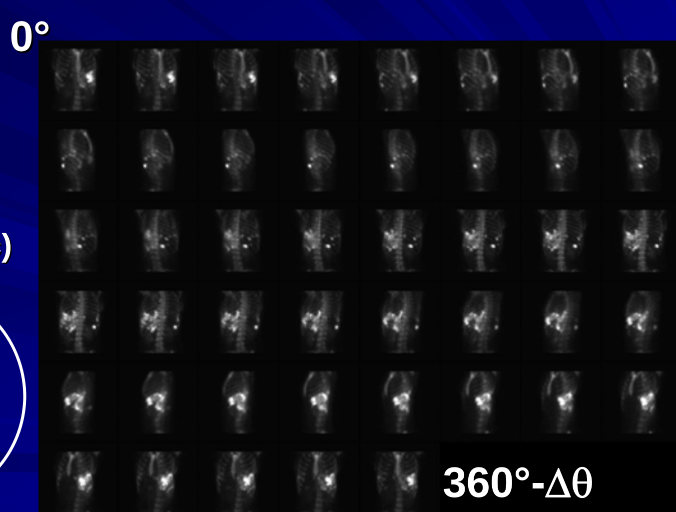
Other Factors

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

SPECT Imaging

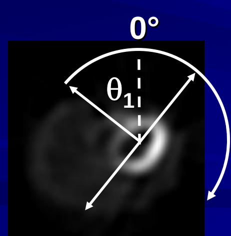
Projections over 360° instead of 180° (exc. cardiac)

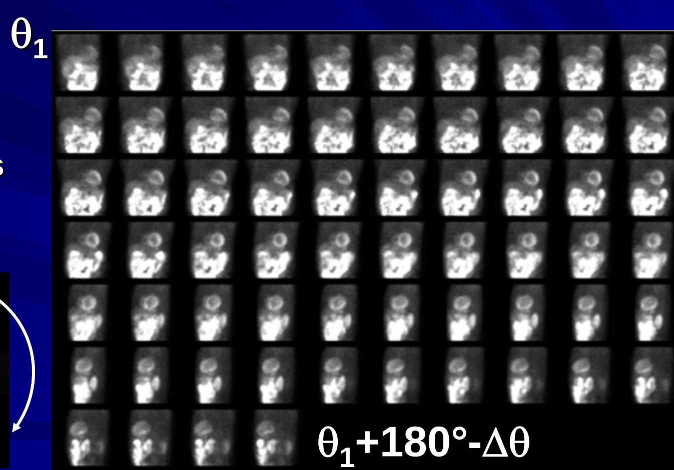




SPECT Imaging

Cardiac SPECT: projections over 180°

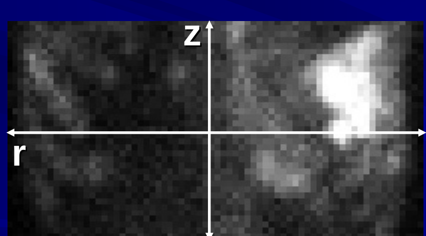




SPECT Imaging

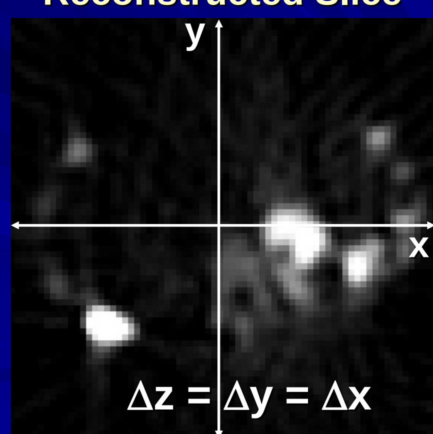
Isotropic Pixels and Voxels

2-D Projection



$\Delta z = \Delta r$

Reconstructed Slice



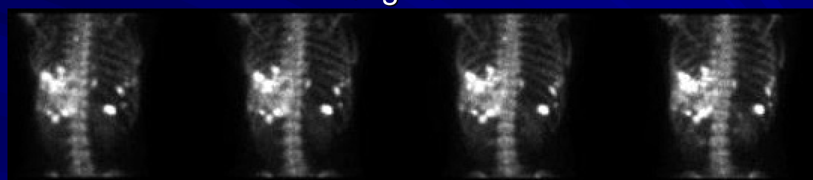
SPECT Imaging

Isotropic Volume Smoothing

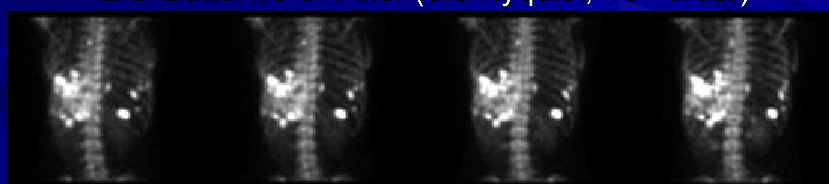
↓ noise amplified by inverse Radon transform ramp filter

2-D filtering of projections ≡ 3-D post-recon filtering

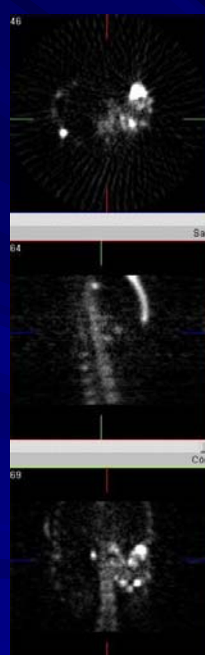
original

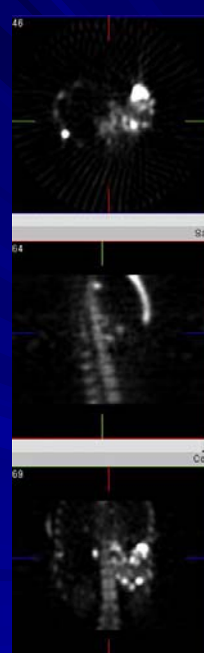


2-D Butterworth Filter (0.6 Nyquist, 10th order)



No volume smoothing

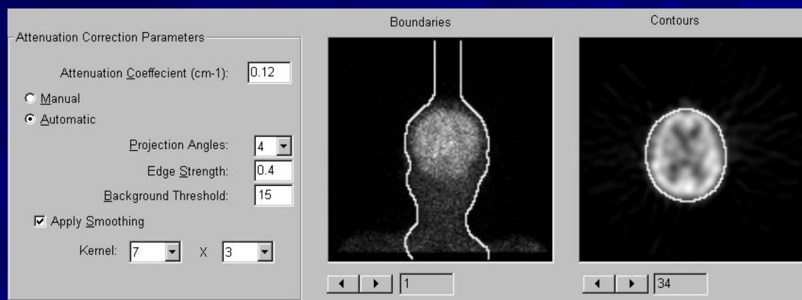


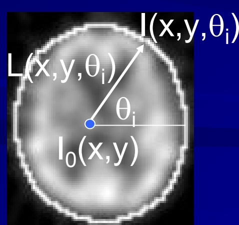


Butterworth 0.6 Nyquist, 10th order

Conventional SPECT AC

Chang post-processing algorithm





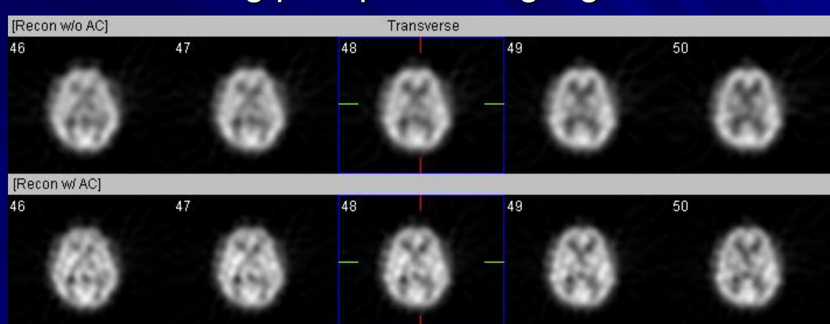
$$I(x,y,\theta_i) = I_0(x,y)\, e^{-\mu L(x,y,\theta_i)}$$

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

($I(x,y)$ = reconstruction w/o AC)

Conventional SPECT AC

Chang post-processing algorithm



- assumes constant μ value (cm^{-1})
- requires accurate anatomical boundary definition
- works reasonably well for brain SPECT
- other body sections problematic
  - variable μ values (esp. in thorax)
  - accurate boundaries difficult to obtain

Conventional SPECT

Filtered Backprojection (FBP) Reconstruction

- 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)

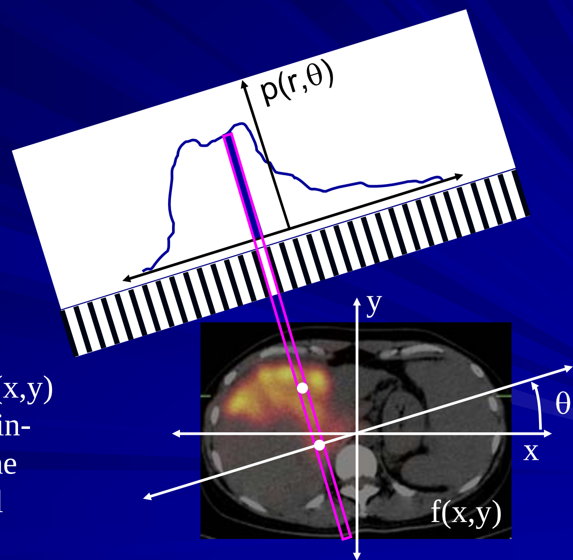
Conventional SPECT

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 μ and, e.g., Chang)
- Doesn't handle depth-dependent resolution
  - (frequency-distance principle has been attempted)

Conventional SPECT

FBP Reconstruction Model



$p(r,\theta) = \Sigma f(x,y)$ 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

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

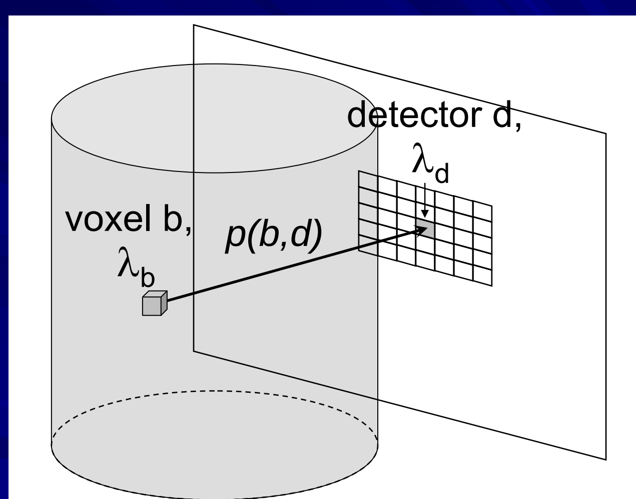
Let *x(b,d)* = # of emissions from *b* measured in *d*

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



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+1th 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 λ that makes the measured outcome most likely.

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

- The maximum likelihood estimator of λ is the measured quantity x.

Maximum (Log) Likelihood

$$l_x(\lambda) = f(y\,|\,\lambda) = \prod_{d=1,\ldots,D} e^{-\sum_{b=1,\ldots,B}\lambda(b,d)} \frac{\sum_{b=1,\ldots,B}\lambda(b,d)^{y(d)}}{y(d)!}$$

$$L_y(\lambda) = \ln l_y(\lambda) = \sum_{d=1,\ldots,D} -\left[\sum_{b=1,\ldots,B}\lambda(b)\,p(b,d) + y(d)\ln\left(\sum_{b=1,\ldots,B}\lambda(b)\,p(b,d)\right) - \ln x(b,d)!\right]$$

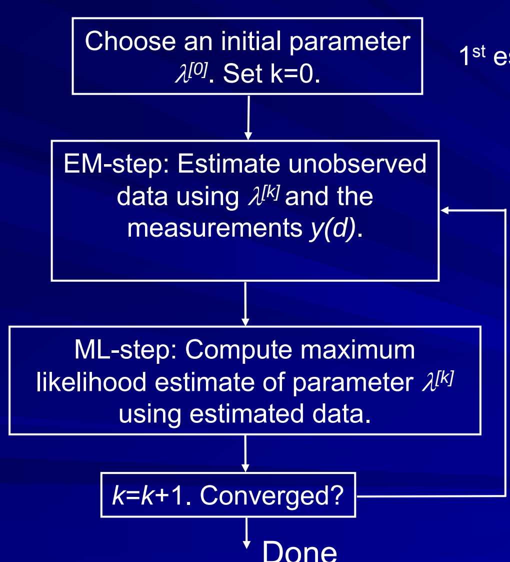
To maximize with respect to $\lambda(b)$,

$$0 = \frac{\partial}{\partial\lambda(b)} L_y(\lambda) \rightarrow -\sum_{d=1,\ldots,D} p(b,d) + \sum_{d=1,\ldots,D}\frac{y(d)\,p(b,d)}{\sum_{b'=1,\ldots,B}\lambda(b')\,p(b',d)}$$

$$\lambda(b)\sum_{d=1,\ldots,D} p(b,d) = \sum_{d=1,\ldots,D}\frac{y(d)\,\lambda(b,d)}{\sum_{b'=1,\ldots,B}\lambda(b',d)}$$

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

ML-EM



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 λ 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

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

The Key to ML-EM

- The probability (or system) matrix in

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

- *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:

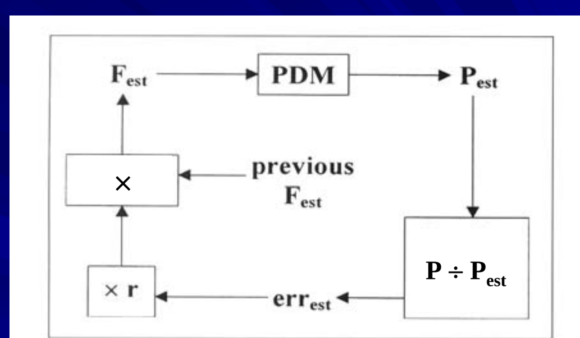
1. Depth-dependent resolution
2. Position-dependent scatter in the patient
3. Depth-dependent attenuation

   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 ML-EM Flow Diagram

F_{est} = recon est.
PDM = p(b,d)
P_{est} = proj. est.
P = measured proj.
err_{est} = proj. est. error
r = damping factor
($0<r\leq1$)



Note: In practice (i.e., in the clinic), the stopping criteria is number of iterations (time constraint) instead of a convergence criteria.

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

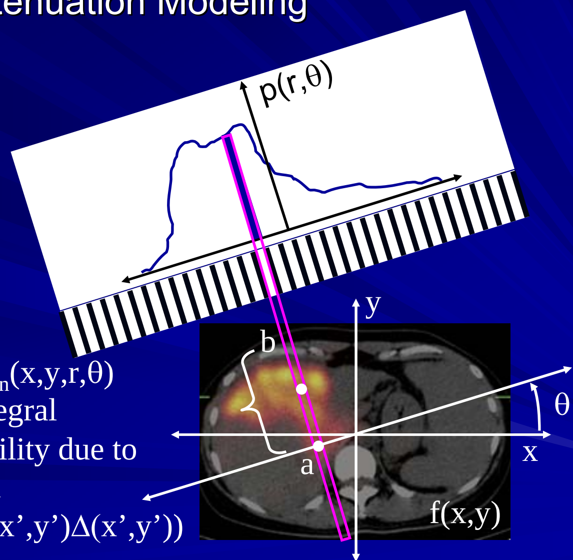
$$\lambda^{[k+1]}(b) = \frac{\lambda^{[k]}(b)\sum_{d=1}^{D}\frac{y(d)\,p(b,d)}{\sum_{b'=1}^{B}\lambda^{[k]}(b')\,p(b',d)}}{\sum_{d=1}^{D}p(b,d) + \beta\left[\frac{\lambda^{[k]}(b)-M(b)}{M(b)}\right]}$$

$M(b)$ obtained from median filter of image of $\lambda^{[k]}(b)$

β = unit-less control parameter

SPECT Iterative Reconstruction

Attenuation Modeling



$p(r,\theta) = \Sigma f(x,y) \times p_{attn}(x,y,r,\theta)$ along a line integral

$p_{attn}(x,y,r,\theta)$ = probability due to attenuation

$p_{attn}(x,y,r,\theta) = \exp(-\Sigma_{ab}\mu(x',y')\Delta(x',y'))$

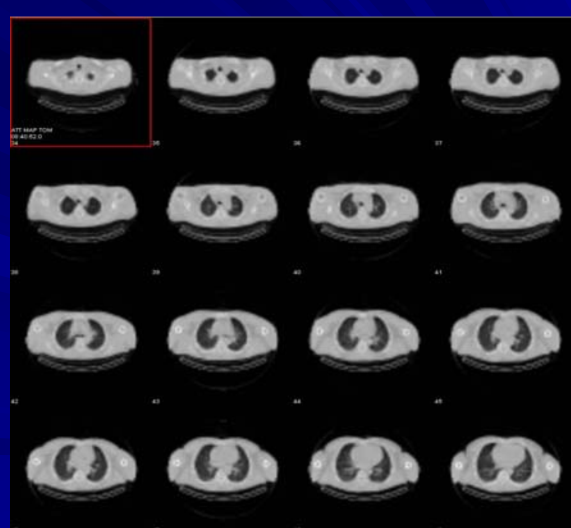
SPECT Iterative Reconstruction

Attenuation Modeling

CT-Based Attenuation Map

<u>(µ map)</u>

Can account for variably attenuating media



SPECT Iterative Reconstruction

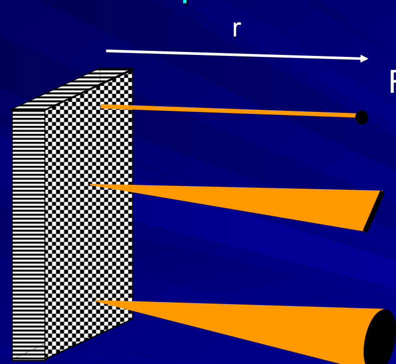
Attenuation Modeling

^{99m}Tc SestaMIBI (Parathyroid adenoma)

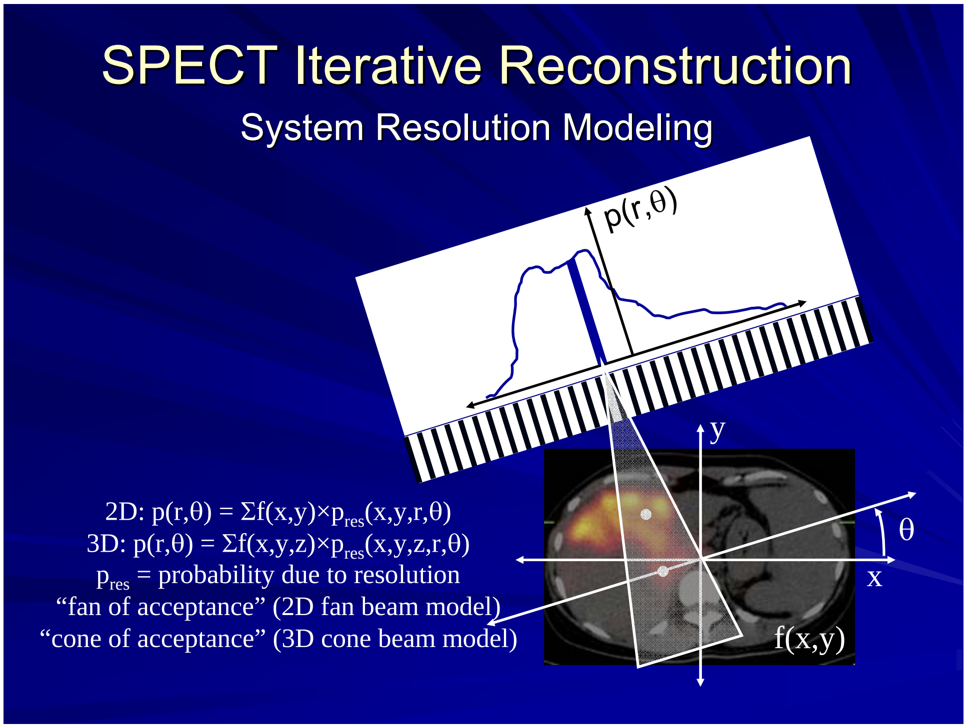
SPECT Iterative Reconstruction

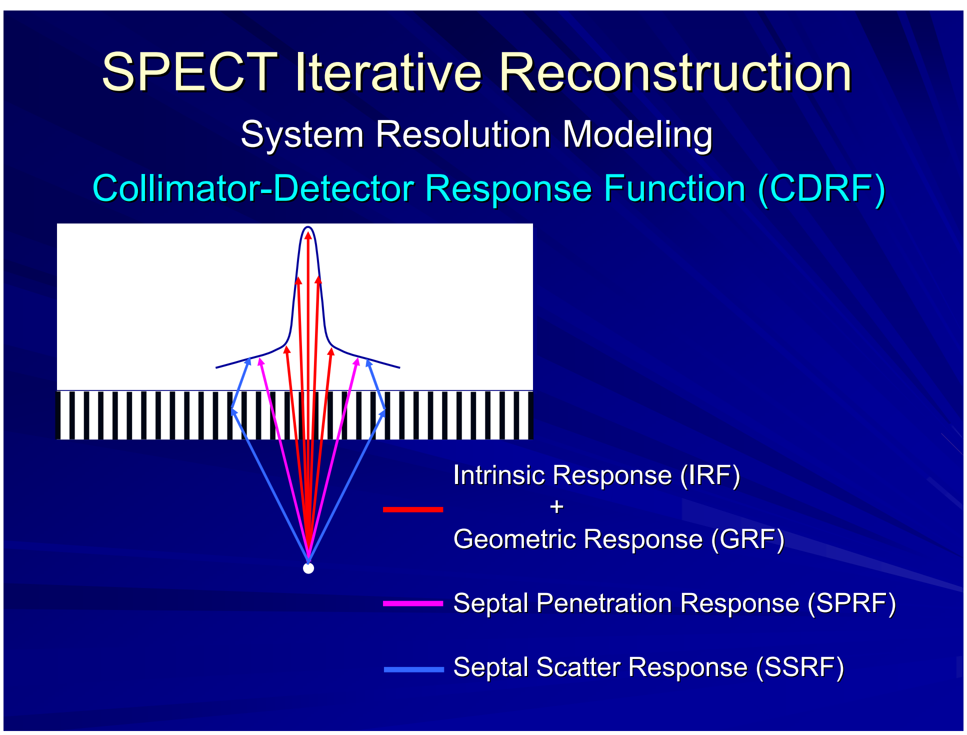
System Resolution (R_s) Modeling

Distance-dependent collimator beam



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


SPECT Iterative Reconstruction
System Resolution Modeling
p(r,θ)
y
θ
x
f(x,y)
2D: $p(r,\theta) = \Sigma f(x,y)\times p_{res}(x,y,r,\theta)$
3D: $p(r,\theta) = \Sigma f(x,y,z)\times p_{res}(x,y,z,r,\theta)$
p_{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

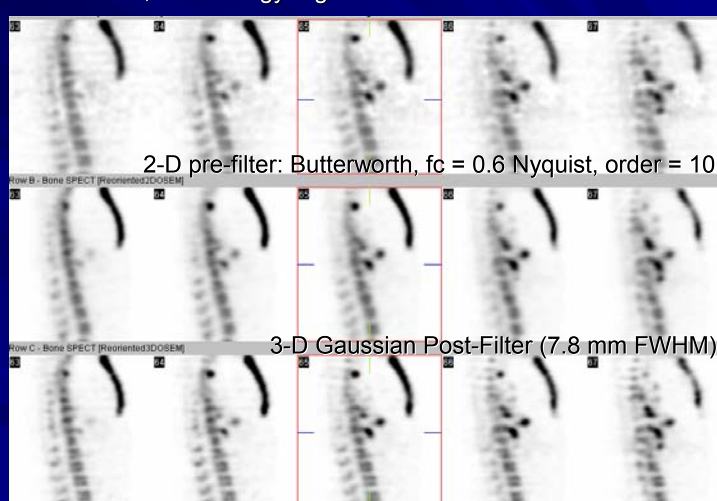
System Resolution Modeling

^{99m}Tc Bone Scan, Low-Energy High-Resolution Collimator

Standard Filtered Backprojection

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

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



SPECT Iterative Reconstruction

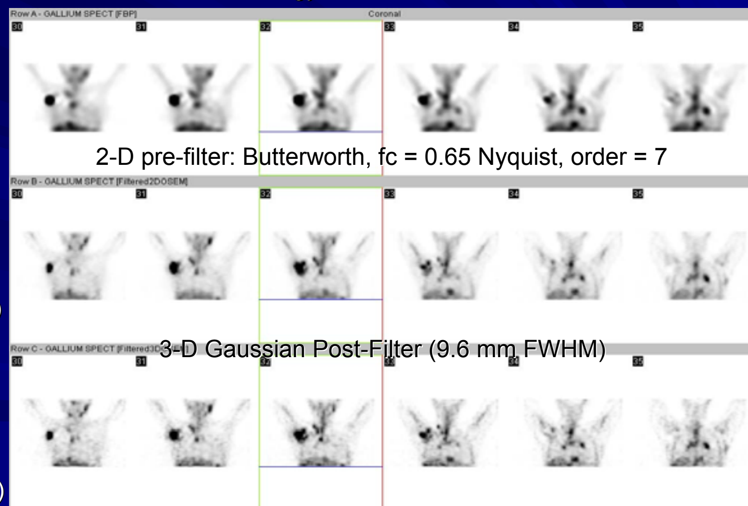
System Resolution Modeling

^{67}Ga Citrate, Medium-Energy Low-Penetration Collimator

FBP

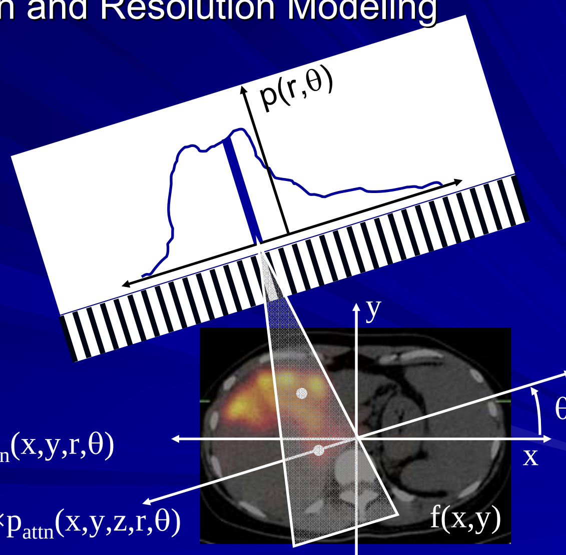
2-D OSEM w/ fan beam modeling (m=12,n=10)

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



SPECT Iterative Reconstruction

Attenuation and Resolution Modeling



2D: $p(r,\theta) = \Sigma f(x,y) \times p_{res}(x,y,r,\theta) \times p_{attn}(x,y,r,\theta)$

3D: $p(r,\theta) = \Sigma f(x,y,z) \times p_{res}(x,y,z,r,\theta) \times p_{attn}(x,y,z,r,\theta)$

SPECT Imaging: Compton Scatter

- Reduces contrast
  - low frequency blur to the image
- Depends on
  - photon energy
  - camera energy resolution, window setting
  - object shapes, ρ'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:

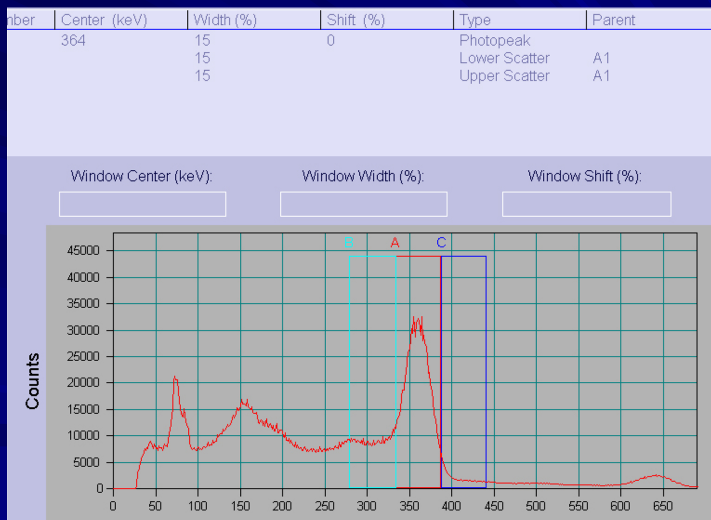
$$S(x,y,\theta) = \Sigma_i \, k_i \times C_i(x,y,\theta)$$

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

k_i = *scatter window image i weighting factor*

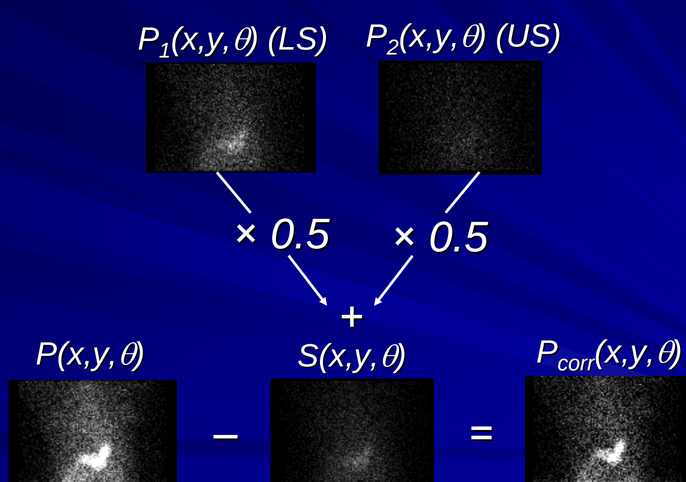
SPECT Iterative Reconstruction

I-131 TEW Scatter Pre-Correction



SPECT Iterative Reconstruction

I-131 TEW Scatter Pre-Correction



SPECT Iterative Reconstruction

DEW/TEW Iterative Scatter Modeling

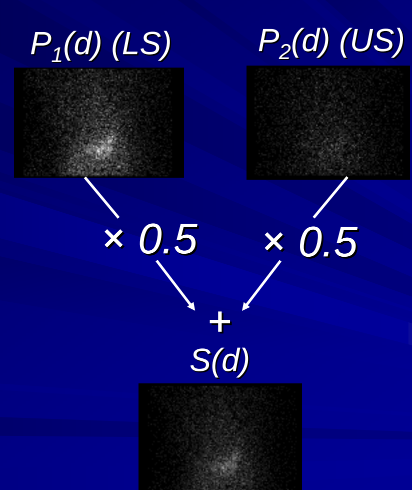
- Estimate scatter contribution to each photopeak projection pixel d, $S(d)$, as a weighted sum of counts, $C_i(d)$, from one (DEW) or two (TEW) adjacent scatter windows
- Incorporate into the forward projection step:

$$P'_{est}(d) \rightarrow P_{est}(d) + S(d)$$

$$S(d) = \Sigma_i \, k_i \times C_i(d)$$

SPECT Iterative Reconstruction

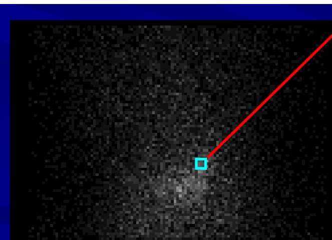
DEW/TEW Iterative Scatter Modeling



SPECT Iterative Reconstruction

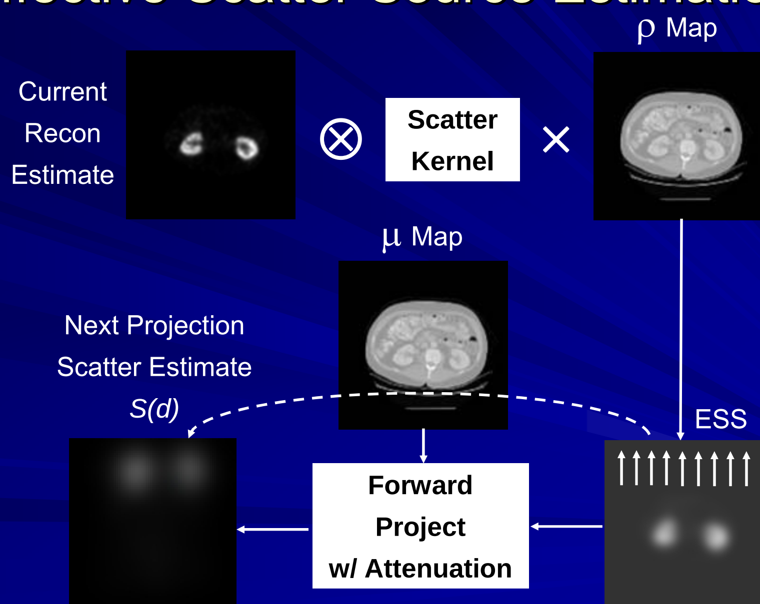
DEW/TEW Iterative Scatter Modeling

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



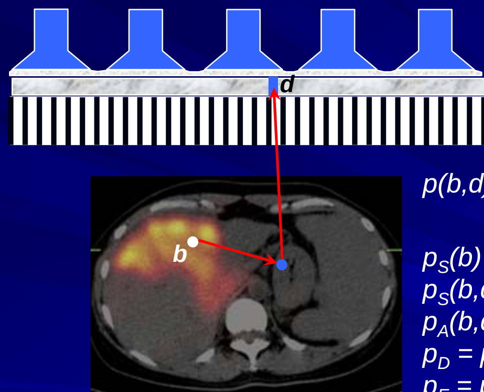
scatter contribution to detector *y(d)* incorporated into forward projector

Effective Scatter Source Estimation



SPECT Iterative Reconstruction

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



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

$p_S(b)$ = prob. of scatter
$p_S(b,d)$ = prob. of scatter into det. d
$p_A(b,d)$ = prob. due to attenuation
p_D = prob. due to det. efficiency
p_E = 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 μ 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 Imaging: Software

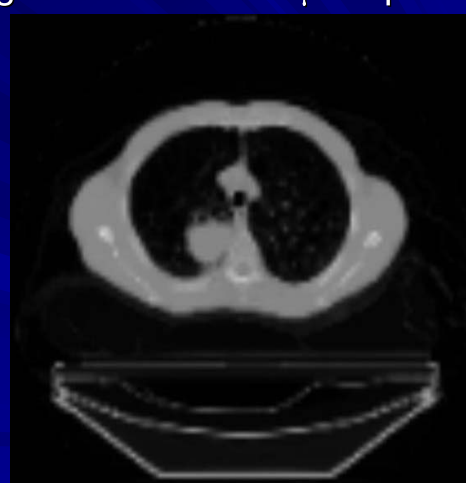
SPECT/CT Image Registration

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 μ Map

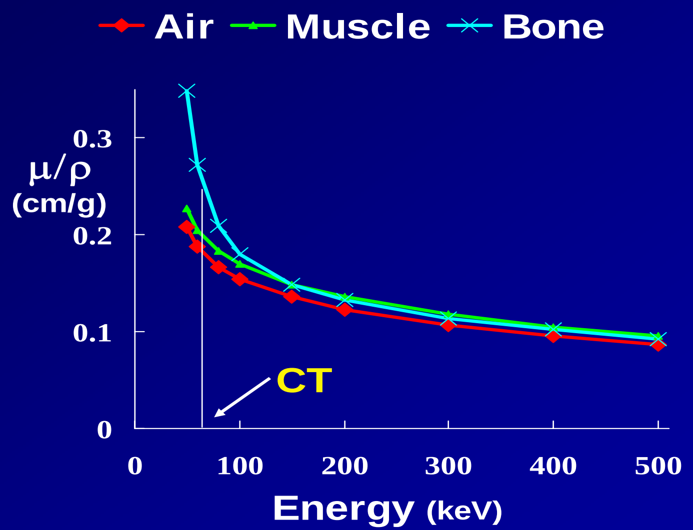
Parameters:
- HU-to-cm^{-1} function
  - piece-wise bilinear (most common)
  - Effective keV
    - CT (~ 70 – 80)
    - SPECT (nuclide dep.)
- Attenuation beam model
  - narrow
  - broad (w/o scatter correction)
- μ map image smoothing



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

CT-Based SPECT μ Values

Material attenuation versus Energy



CT-Based SPECT μ Values

Example CT HU-to-SPECT cm^{-1} transform

(standard: piece-wise bilinear function)

	keV
CT:	75 (effective)
SPECT:	140 (^{99m}Tc)

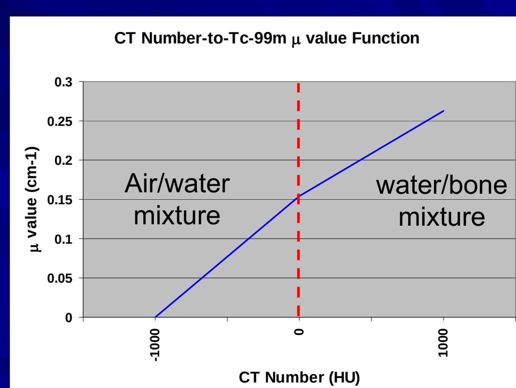
Transform

$$\mu_{140}(m) = \frac{[HU+1000]\times\mu_{75}(H_2O)}{1000\times[\mu_{75}(m)/\mu_{140}(m)]}$$

$\mu_{75}(H_2O)$

0.188 cm^{-1}

material m	$[\mu_{75}(m)/\mu_{140}(m)]$
	1.22 (HU $\leq$ 0)
	1.43 (HU > 0)



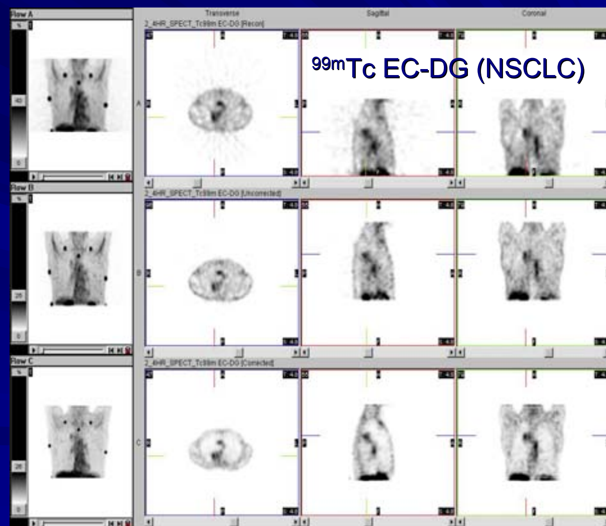
SPECT/CT Imaging: Software

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"

Scanning Lines

Stationary Lines

Limitations

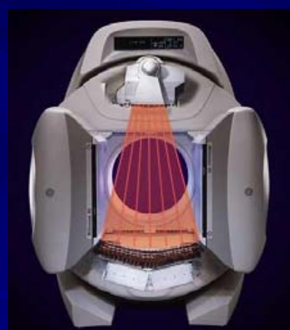
1. Poor resolution/partial volume (esp. air, lung, soft tissue, bone interfaces)
2. Poor statistics (noisy images, heavy smoothing)
3. Dead-time (imaged with gamma camera detector)
4. Emission Contamination (e.g., Tc-99m downscatter)
5. Designed for cardiac

Supplanted by SPECT/X-ray CT

SPECT/CT Imaging: Hardware

Hawkeye® (GE Healthcare)

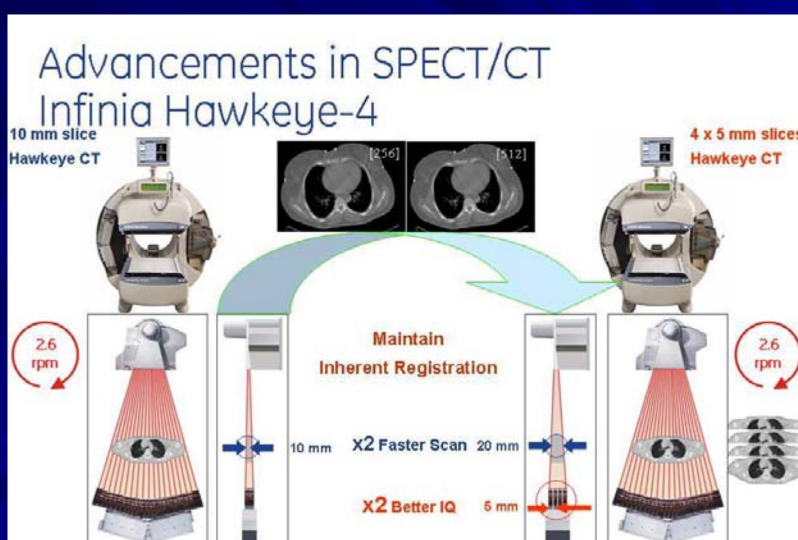
Hawkeye®
(Original 1-slice CT)



Infinia / ^{VC} Hawkeye-4
(Current 4-slice CT)

Slide courtesy of Osnat Zak, GE Healthcare

SPECT/CT Imaging: Hardware



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)

	Hawkeye4	Hawkeye4	Conventional CT
X-ray tube voltage	140 kVp	140 kVp	120-140 kVp
Tube current	1mA	2.5mA	20-80 mA
Patient dose	0.72 mSv	1.8 mSv	>6.5 mSv

Slide Courtesy of Osnat Zak, GE Healthcare

SPECT/CT Imaging: Hardware

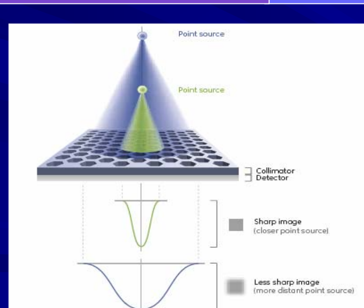
GE Hawkeye: Bone WB 15 min | x 1 SPECT View 20 min | 40cm CT AC + Anatomy 10 min — 45 Minutes

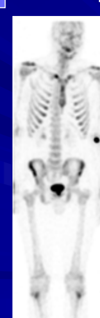
GE Hawkeye-4 Evolution for Bone: Bone WB 15 min | x 1 SPECT Views 10 min | 40cm CT AC + Anatomy 5 min — 30 Minutes

GE Hawkeye-4 Evolution for Bone: x 3 SPECT Views 30 min | 80 cm CT AC + Anatomy 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

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

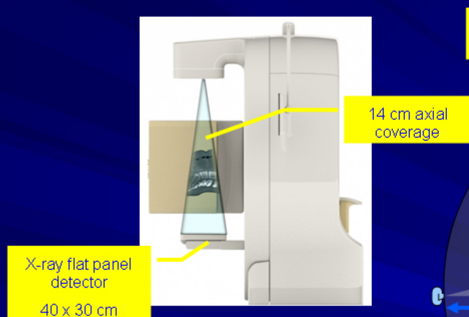
BrightView XCT (Philips Healthcare)

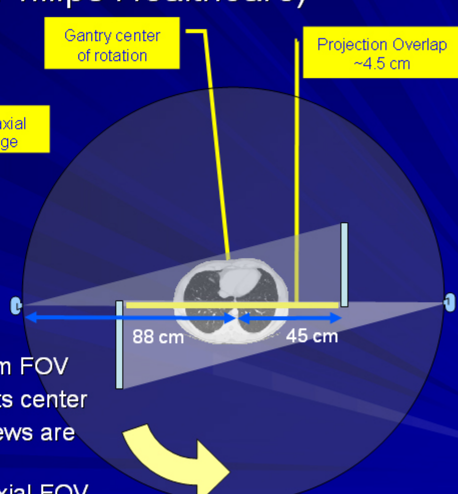
- Flat Panel Volume CT technology
- Coplanar with SPECT Imaging
  - (cardiac -14 cm)
- Localization, CT-AC, Bone Imaging
- Max. Rotation Speed
  - 12 sec for 360º (14 cm axial FOV)
- Slice thickness
  - 0.33 – 2.0+ mm (isotropic voxel)
- Resolution: >15 lp/cm
- Dose (CTDI) - Typical:
  - ~6 mGy (body 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 recons using GPU
- Volumetric CT system goals
  - X-ray cone-beam overlaps SPECT FOV
  - 360^{o} 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: Hardware

BrightView XCT (Philips Healthcare)





- Detector effectively 2x in size for 47 cm FOV
- Flat panel offset ~17.4 cm relative to its center
- Half projections from 180^{o} opposite views are weighted and combined
- 3 XCT spins to cover 40 cm SPECT axial FOV

Slide Courtesy of Ling Shao, Philips Healthcare

SPECT/CT Imaging: Reconstruction

Astonish (Philips Healthcare)

FBP

- 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

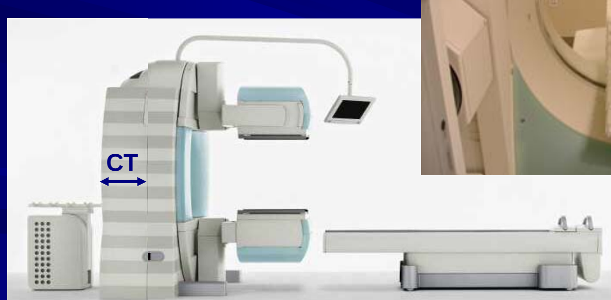
Astonish

Slide Courtesy of Ling Shao, Philips Healthcare

SPECT/CT Imaging: Hardware

Symbia® T (Siemens Medical Solutions USA)

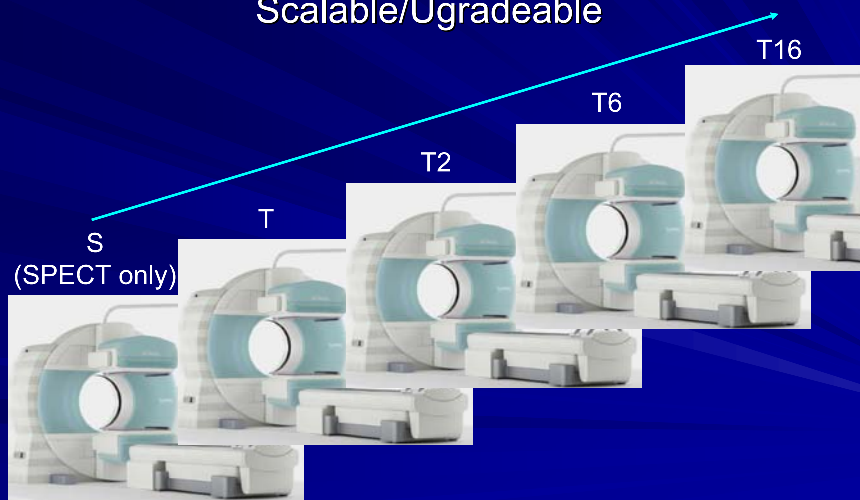
1-, 2-, 6- or 16-slice CT



SPECT/CT Imaging: Hardware

Symbia® T (Siemens Medical Solutions USA)

Scalable/Ugradeable



SPECT/CT Imaging: Hardware

Symbia® T (Siemens Medical Solutions USA)

	T	T2	T6	T16
Collimation (mm)	2×1.0 to 2×5		6×0.5 to 6×3	16×0.6 to 16×1.2
Max. speed (360º)	0.8 s		0.6 s	0.5 s
Slices/rotation	2		6	16
kVp	80, 110, 130			
mA*	30 – 240		20 - 345	
Slice width (mm)	3, 5, 8	1 - 10	0.63 - 10	0.6 - 10
FOV (cm)	50 (512 × 512 = 0.98 × 0.98 pixels) up to 200 (axial)			
Patient Port	70 cm			

*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)

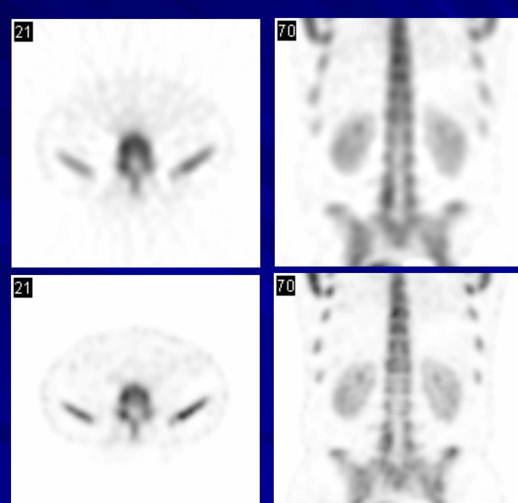
- Flash3D OSEM Reconstruction
  - 3D collimator resolution compensation
    - in both forward and back-projection directions
    - 3D Gaussian PSF v. distance from collimator
  - Attenuation compensation (CT-based AC maps)
  - Scatter compensation
    - DEW/TEW-based scatter projection images
    - Additive 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: Reconstruction

Flash3D (Siemens Medical Solutions USA)

FBP

Flash3D



SPECT/CT Imaging: AC Map

Multi-γ Radionuclide (GE Hawkeye 1-Slice)

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

$$\mu(\gamma_{low}) = \mu(\gamma_{high}) \times \alpha_{low}$$

$$\alpha_{low} = \mu(H_2O,low) / \mu(H_2O,high)$$

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

$$AF = e^{-\int \mu(L_\theta) dL_\theta)}$$

$$AF(x,y,\theta)_{multi\gamma} = \Sigma\, W_{\gamma i} \times AF_{\gamma i}\ (W_{\gamma i} = \text{rel. Wt. of } \gamma i)$$

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

(Note: bone attenuation will be underestimated)

SPECT/CT Imaging: AC Map

Multi-γ Radionuclide (Siemens Symbia T)

^{111}In

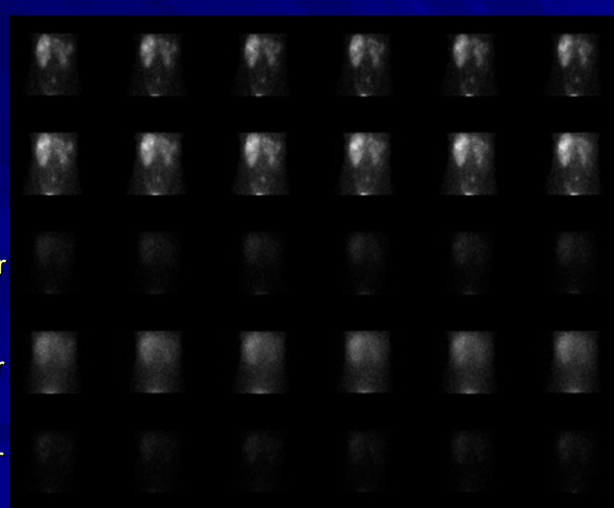
172 keV photopeak

247 keV photopeak

172 keV lower scatter

172 keV upper scatter

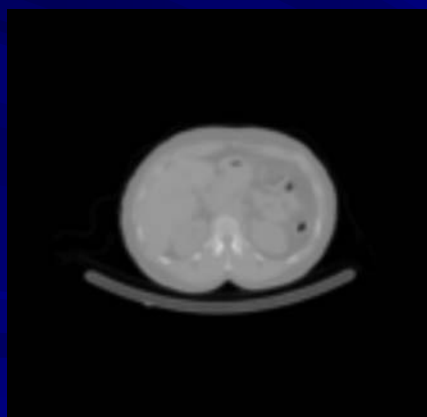
247 keV lower scatter



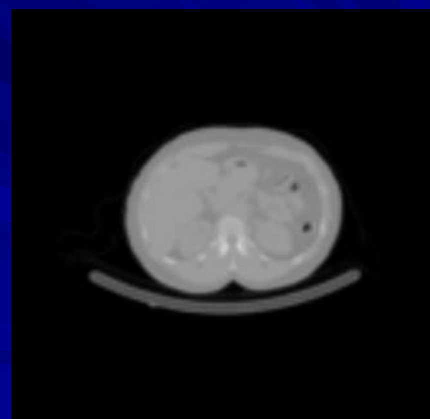
SPECT/CT Imaging: AC Map

Multi-γ Radionuclide (Siemens Symbia T)

^{111}In 172 keV photopeak



^{111}In 247 keV photopeak



SPECT/CT Imaging: Hardware

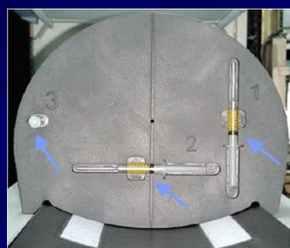
NM-CT FOV Calibration

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: Δx, Δy, Δz, $\Delta\alpha$, $\Delta\beta$, $\Delta\gamma$
5. Calibration for each set of collimators and detector configuration (180° and 90°) may be required

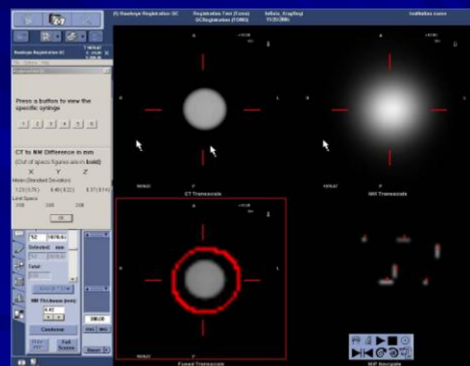
SPECT/CT Imaging: Hardware

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 (^{m99}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

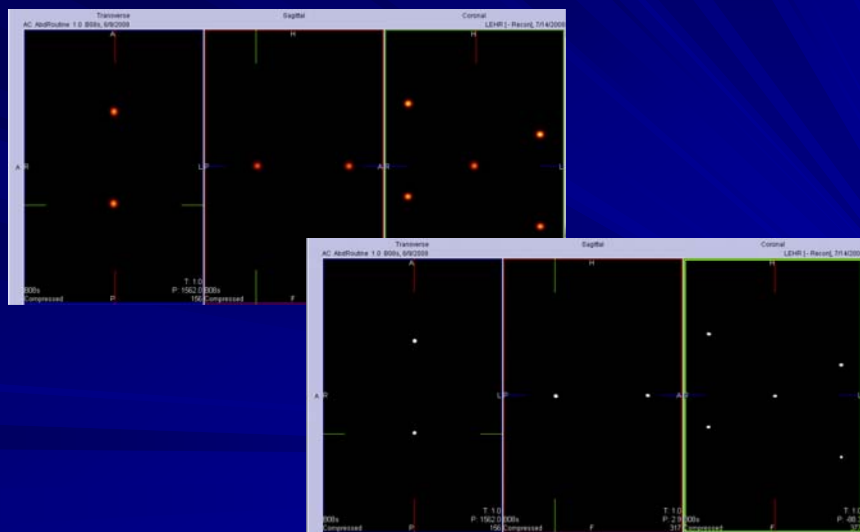
- 10 point sources
- Spiked with:
  - CT contrast material
  - Tc-99m activity

Cotton swab tip in plastic vial

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

SPECT/CT Imaging: Hardware

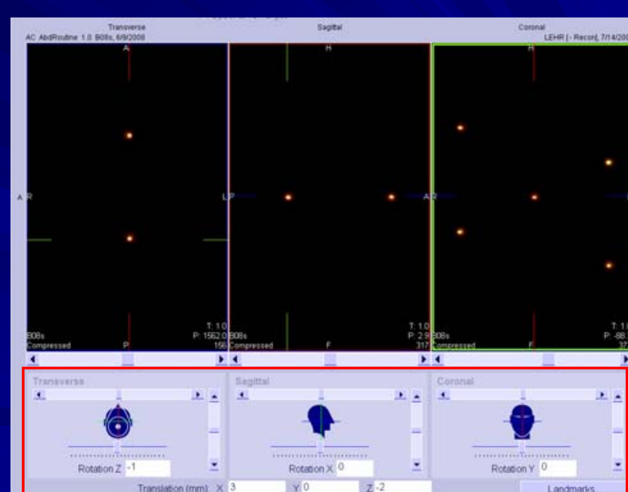
NM-CT FOV Calibration: Siemens Symbia



SPECT/CT Imaging: Hardware

NM-CT FOV Calibration: Siemens Symbia

Iteratively solve for transformation matrix

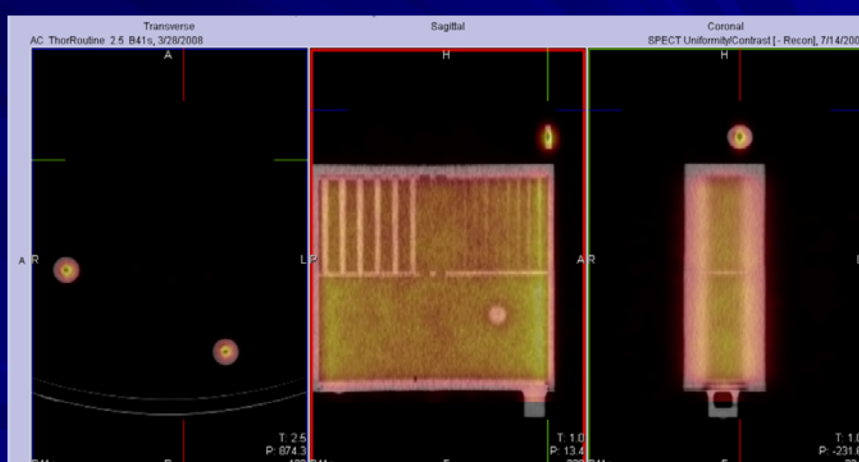


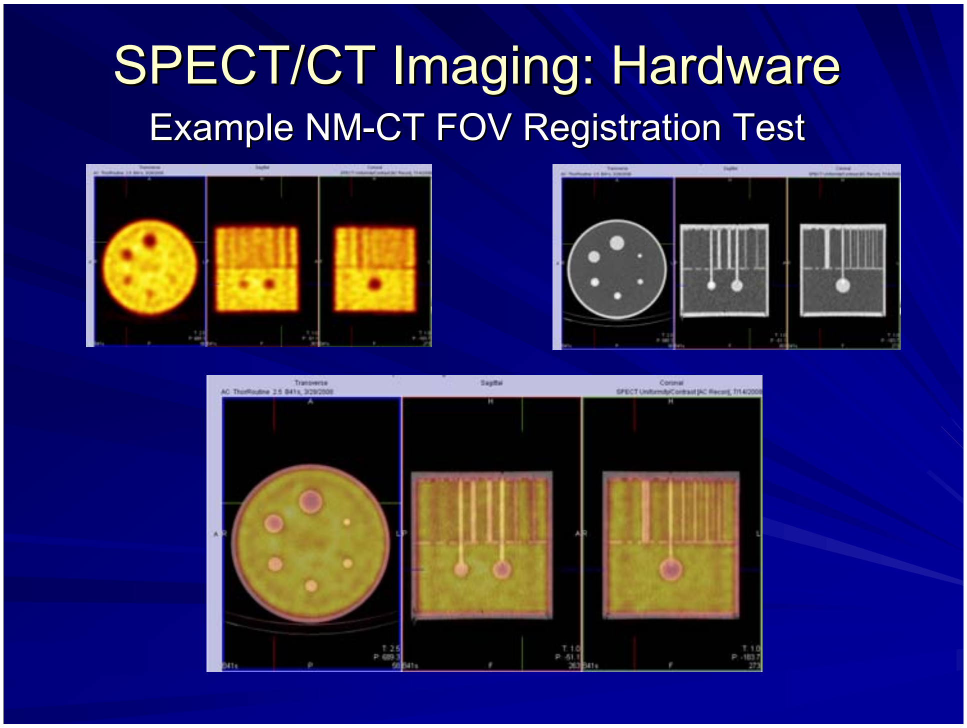
SPECT/CT Imaging: Hardware

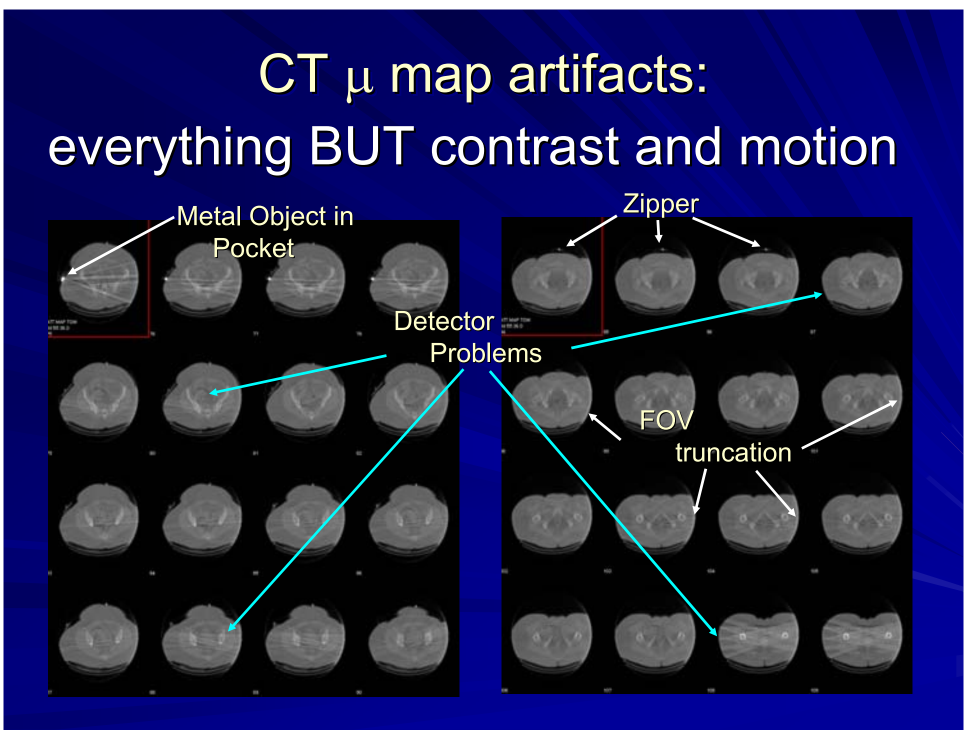
Example NM-CT FOV Registration Test

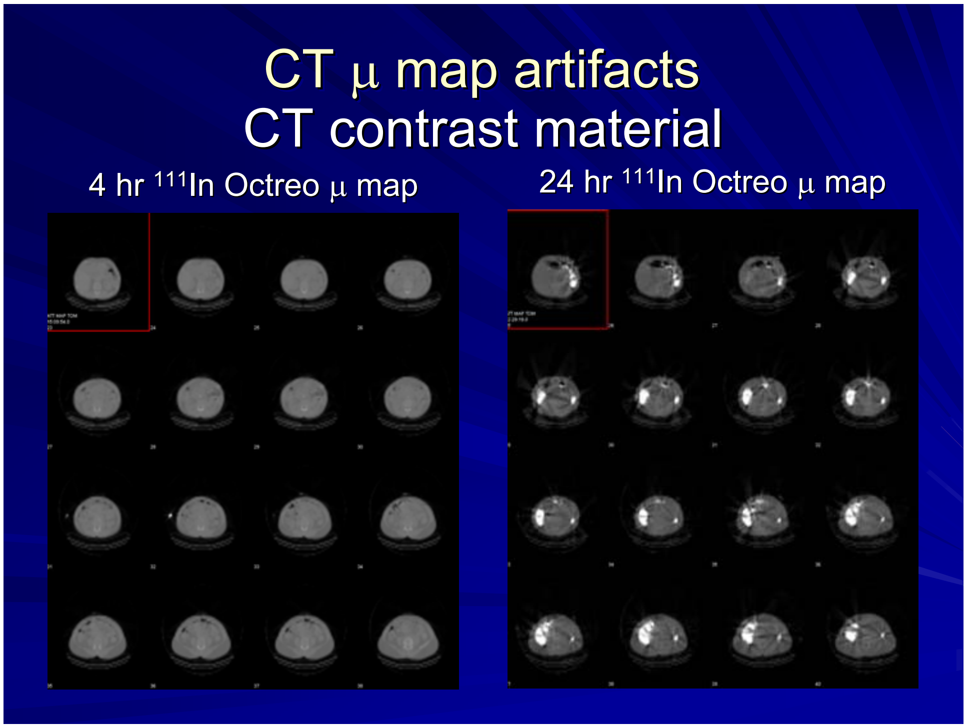
SPECT/CT Imaging: Hardware

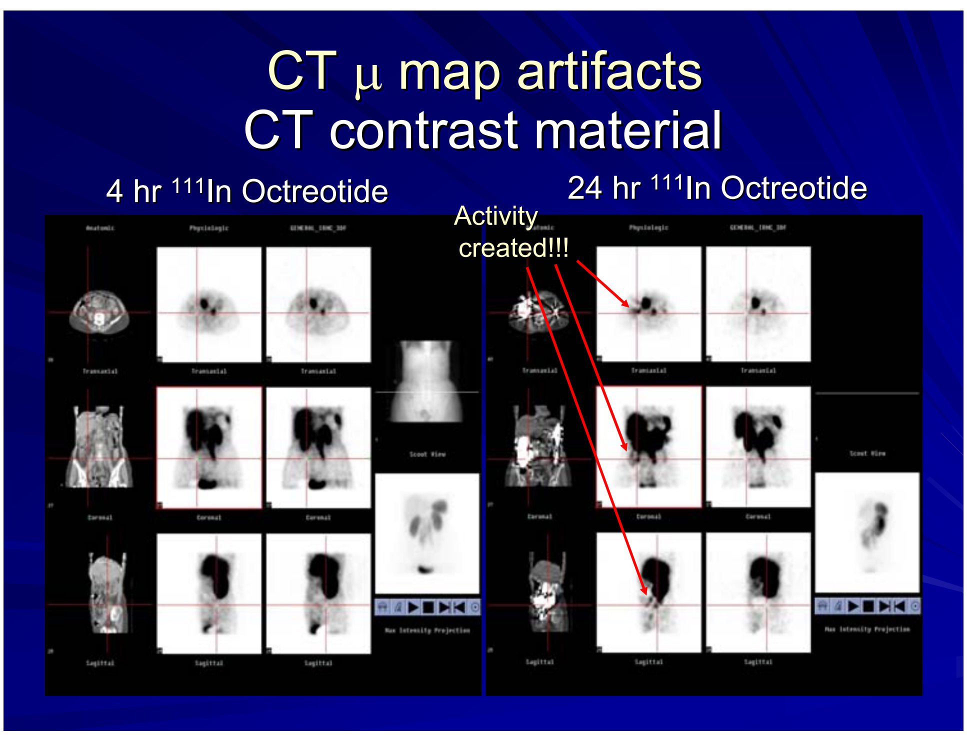
Example NM-CT FOV Registration Test




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


CT μ map artifacts:
everything BUT contrast and motion
Metal Object in Pocket
Zipper
Detector Problems
FOV truncation

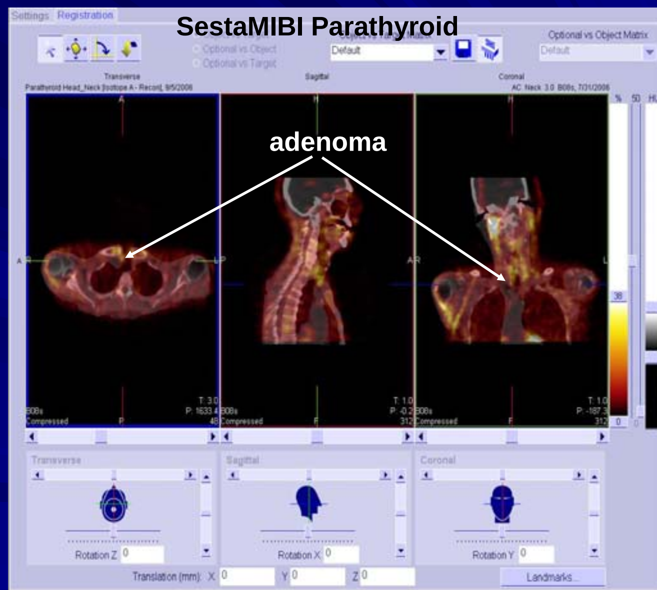

CT μ map artifacts
CT contrast material
4 hr 111In Octreo μ map
24 hr 111In Octreo μ map


CT μ map artifacts
CT contrast material
4 hr 111In Octreotide
24 hr 111In Octreotide
Activity created!!!

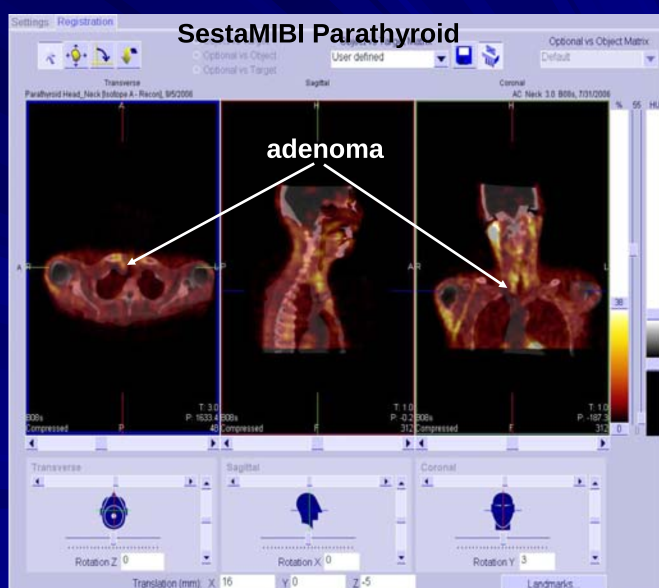
SPECT/CT: Motion

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

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



SPECT/CT: Motion Correction



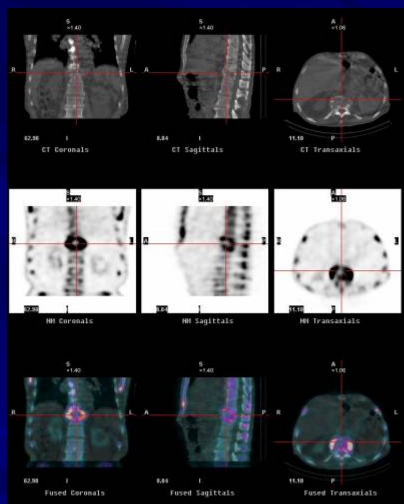
Clinical SPECT/CT

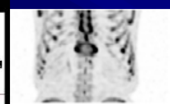
- Attenuation Correction
  - General NM
  - Cardiac
- Tumor Localization
  - Anatomical overlay on functional image
- Improved Diagnostic Accuracy (bi-directional)
  - CT: Density, Morphology, Structure (e.g., skeletal)
  - SPECT: Physiology
  - Additional anatomical information added to SPECT
  - Additional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

SPECT Applications (numerous)

- Stress/Rest Myocardial Perfusion Imaging of CAD
  - Stress: ^{99m}Tc-sestaMIBI or ^{99m}Tc-Tetrafosmin   Rest: ^{99m}Tc-labeled agents or ^{201}Tl chloride
- ^{99m}Tc-MDP: bone diseases, cancer metastatic to bone
- ^{111}In-Octreotide: neuroendocrine cancers
- ^{123}I-MIBG: pheochromocytoma, neuroblastoma
- ^{99m}Tc-sestaMIBI: parathyroid adenomas
- ^{67}Ga-Citrate: inflammation, lymphoma
- ^{111}In-ProstaScint: prostate cancer
- ^{131}I-NaI: thyroid cancer (diagnosis, dosimetry, treatment planning)
- ^{99m}Tc-sulfur colloid: lymphoscintigraphy, liver/spleen
- ^{99m}Tc-red blood cells: hemangioma
- ^{99m}Tc-/In-111 white blood cells: infection, lymphoma
- ^{99m}Tc-HMPAO, -ECD: brain perfusion
- ^{201}Tl chloride: tumor perfusion (e.g., brain)
- ^{111}In-Zevalin, ^{153}Sm-EDTMP: dosimetry, treatment planning

Tc-99m Bone SPECT/CT (Hawkeye)





Hawkeye-4 with **Evolution for Bone** Advanced Reconstruction

Tc-99m Bone Study

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.

Images Courtesy of Tel-Aviv Sourasky Medical Center

Slide Courtesy of Osnat Zak, GE Healthcare

Tc-99m MDP Bone (BrightView)

- 202 lbs (92 kg), Male, 25 yrs, Dx: Right knee sarcoma, One 24-s CT

CT parameters:	SPECT parameters:
120 kVp/80 mA	25.3 mCi Tc-99m MDP, 3 hrs p.i.
10 ms pulse, 14.9 mGy $CTDI_{VOL}$	128 x 128 , 128 views, 20 s, 1.4 zoom

CT resampling:

0.64 mm voxels

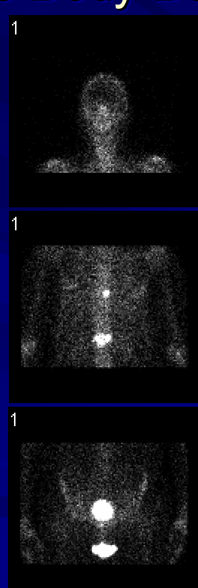
Images courtesy of Radiological Associates of Sacramento

Slide Courtesy of Ling Shao, Philips Healthcare

WB Bone SPECT/CT: CT First (Symbia)

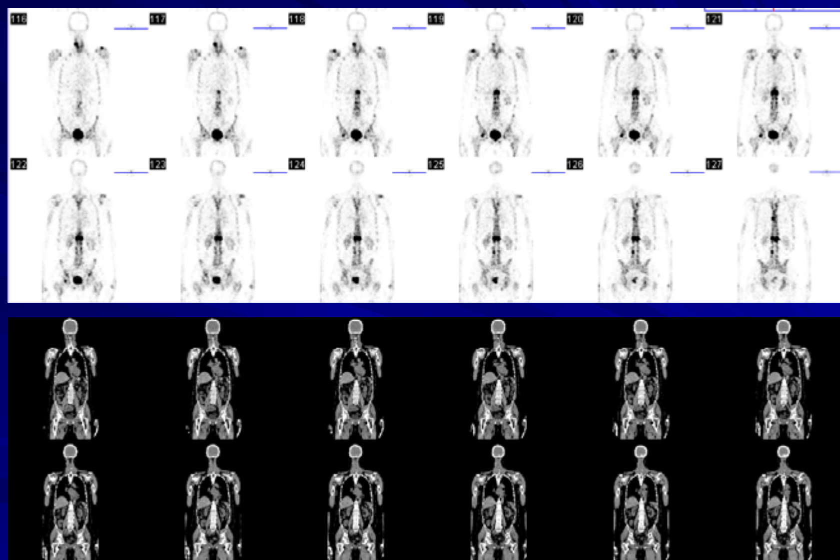
- Top of head-to-mid thigh
- 36.4 cm axial FOV per bed
- CT scan length set to 109.2 cm (36.4 cm × 3)
- CT scan FOV adjusted axially
- Max. CT recon FOV (50 cm)
- 2.5 mm thick/2 mm increment
- Followed by 3-bed SPECT over same axial FOV

Whole Body Bone SPECT Acquisition

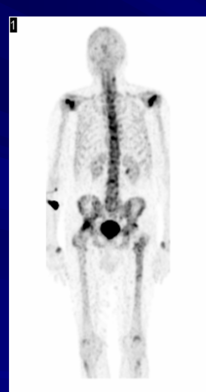


- NCO Continuous Acquisition
- 180 views x 5 sec/view
- 7.5 min total acquisition time/bed
- 3 beds: 25 min
- 4 beds: 34 min
- Recon: 15 ss/8 iters 8 mm filter

Whole Body Bone SPECT/CT



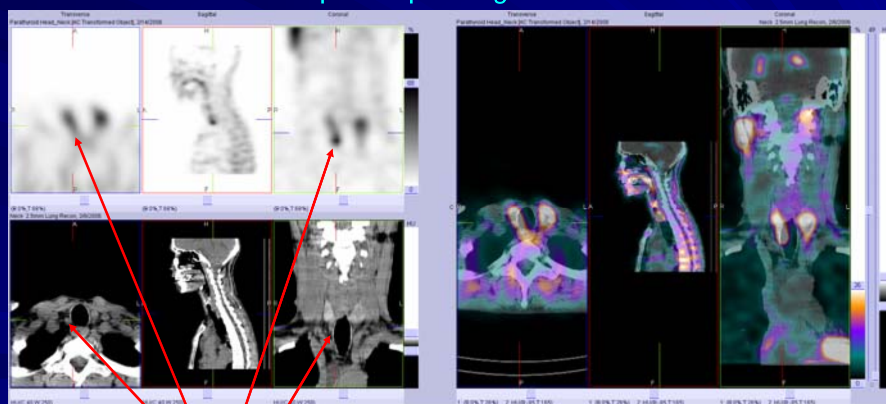
4-Bed Bone SPECT/CT (Symbia)



Tc-99m SestaMIBI (Symbia)

Parathyroid Adenoma – Surgery Planning

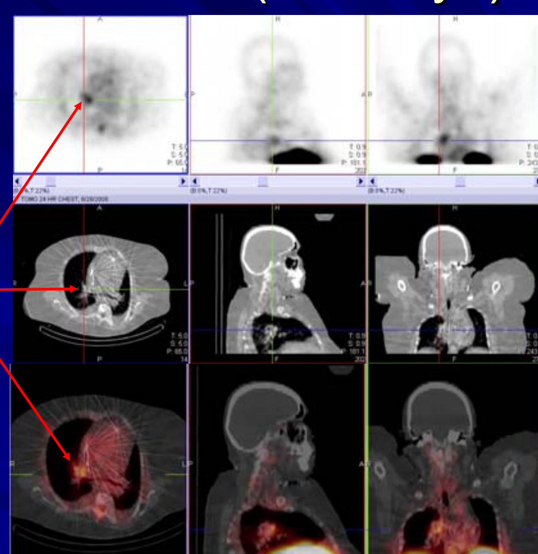
1.25 mm thick/1.0 mm increment 25 cm FOV CT
recon for improved pre-surgical localization



Parathyroid adenoma localized with SPECT/CT

In-111 Octreotide (Hawkeye)

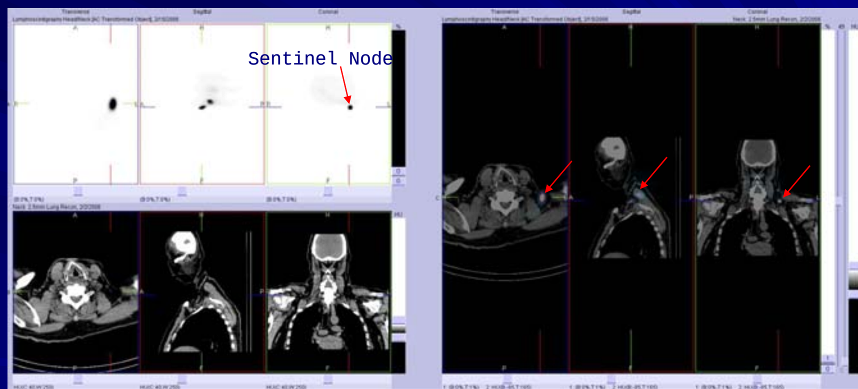
Neuroendocrine
tumor
localization



Images Courtesy of Mark Madsen, Dept of Radiology, U. of Iowa MC

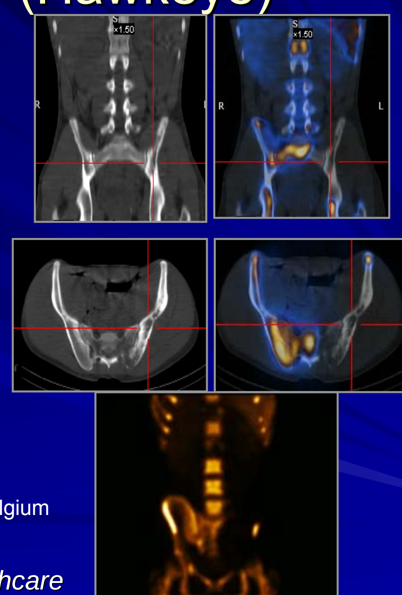
Tc-99m SC Lymphoscintigraphy

Sentinel Lymph Node – Pre-Surgical Localization



Melanoma in the left upper back

Tc-99m WBC (Hawkeye)



Malignant lymphoma

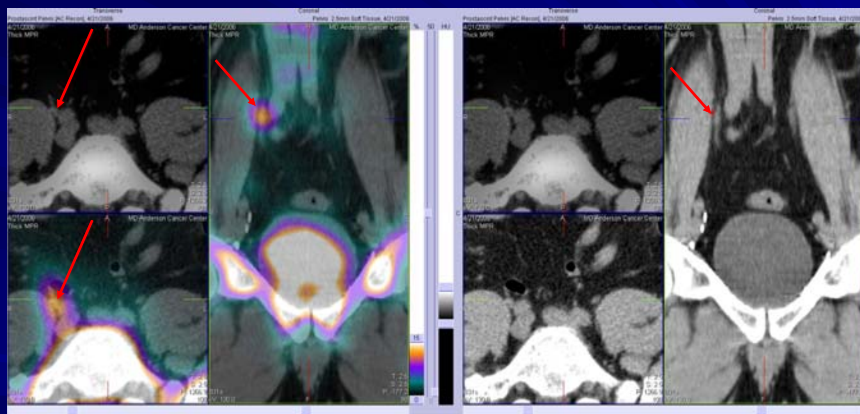
- **Clinical History:**
  - Man aged 22. Lower back pain and decreased general condition.
- **Findings:**
  - White bloodcell scintigraphy. SPECT shows medullary destruction at level of D12, L2, S1 and the left iliaca bone. Hawkeye CT shows heterogeneous bone structure, Paget-like, in the concerned area's 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

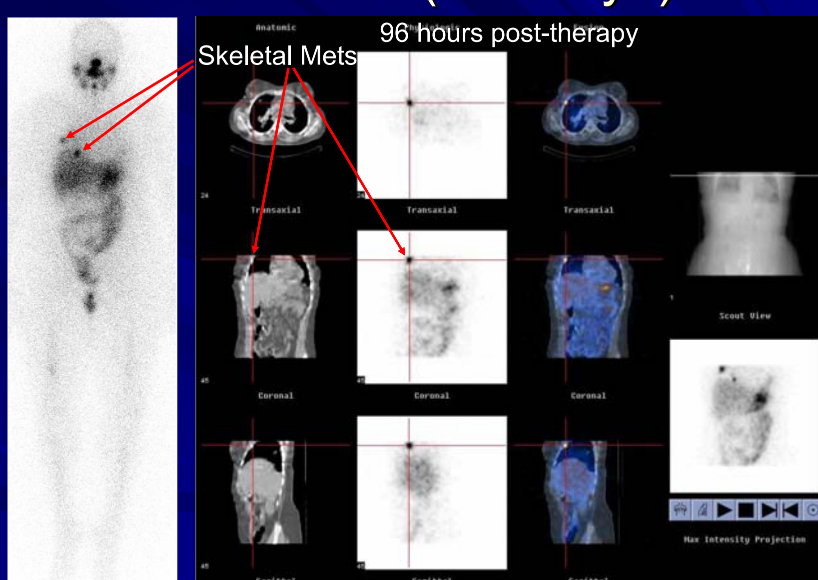
In-111 ProstaScint (Symbia)

96-hour SPECT/CT



Suspicious finding on SPECT = metastatic node on SPECT/CT

I-131 NaI (Hawkeye)



Cardiac SPECT/CT (BrightView)

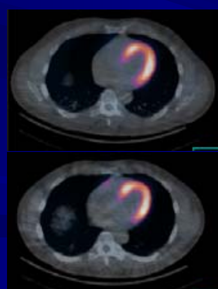
- 194 lbs (88 kg) , Male, 49 yrs, Dx: Pre-op clearance, Abnormal EKG
- 60-second CT, tidal breathing and 12-second CT, end expiration BH

CT parameters:

60 second	12 second
120 kVp/5 Ma	120 kVp/2.5 mA
10 msec pulse width	continuous
1.2 mGy $CTDI_{VOL}$	0.79 mGy $CTDI_{VOL}$

SPECT parameters:

Persantine stress, 2.5 hrs p.i.
35 mCi Tc-99m MIBI
64 x 64, 64 azimuths
20 sec/azimuth, 1.46 zoom

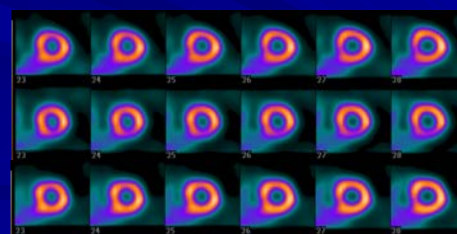


Images courtesy of Radiological Associates of Sacramento

12 s

no AC

60 s

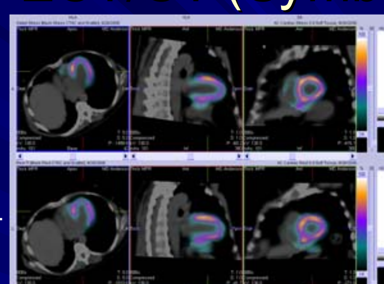


Slide Courtesy of Ling Shao, Philips Healthcare

Cardiac SPECT/CT (Symbia)

Tc-99m SPECT/CT

Tl-201 SPECT/CT

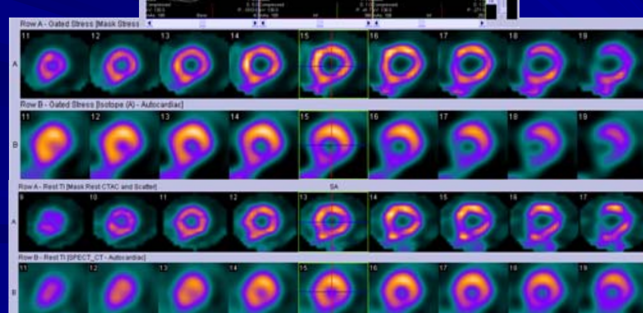


Tc-99m 3DOSEM

Tc-99m FBP

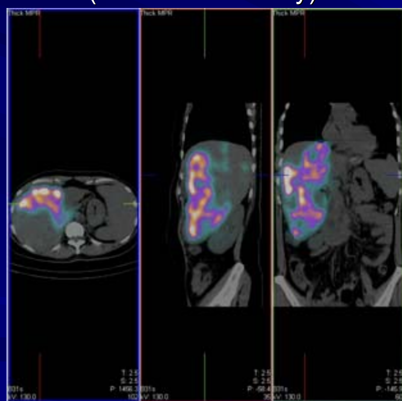
Tl-201 3DOSEM

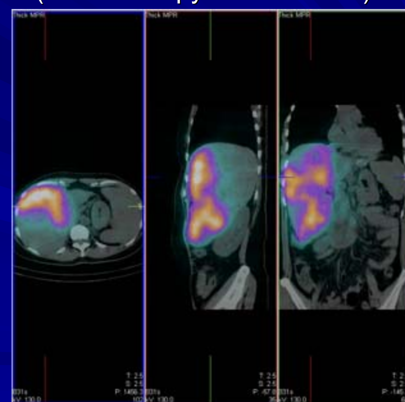
Tl-201 FBP



Y-90 Microspheres SIRT (Symbia)

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

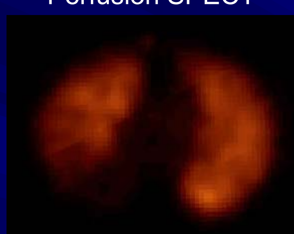




Tc-99m MAA Perfusion (Symbia)

Lung Function-Based IMRT Treatment Planning

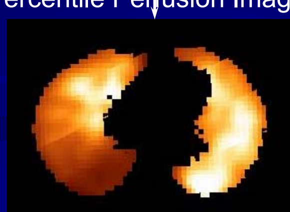
Perfusion SPECT

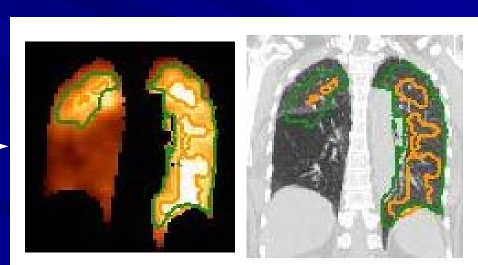


= 50^{th} percentile contour (top 50% of pixels)

= 90^{th} percentile contour (top 10% of pixels)

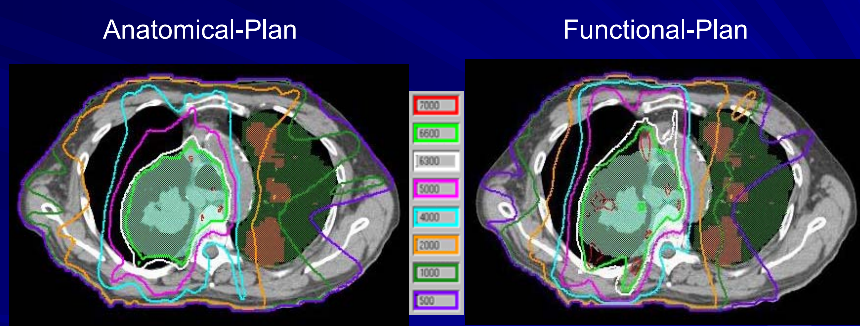
Percentile Perfusion Image





Tc-99m MAA Perfusion (Symbia)

Lung Function-Based IMRT Treatment Planning



Shioyama, et al, Int J Radiation Oncology Biol Phys 2007, 1249 - 1258

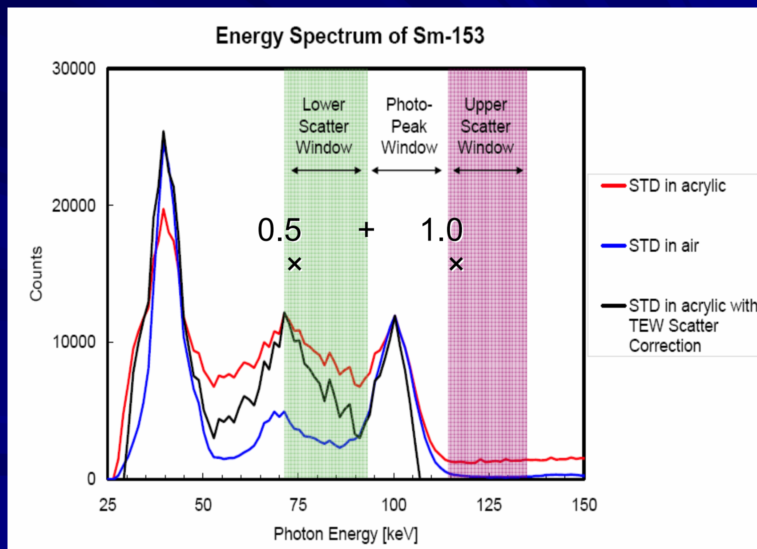
Sm-153 EDTMP (Symbia)

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

TEW Scatter Est.

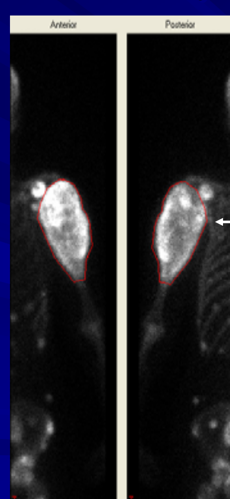


Sm-153 EDTMP Planar Imaging

L Shoulder Tumor Activity (cts) vs. Time

Geometric Mean of Net Counts

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



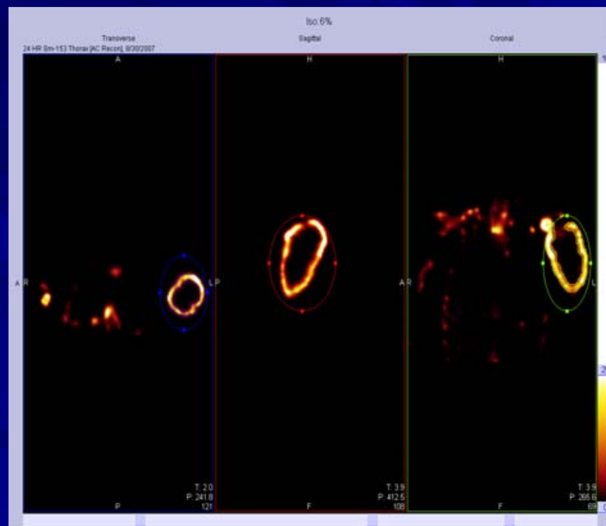
Sm-153 Quantitative SPECT

Tumor Volumetric Analysis

<u>SPECT Tumor Estimates (6% threshold)</u>

Volume (683 cc)

Counts @ 24 h



Sm-153 SPECT/CT

Sensitivity Calibration (Cts/uCi)

Standard: ~1 mCi in 10 ml

(in abdominal scatter phantom)

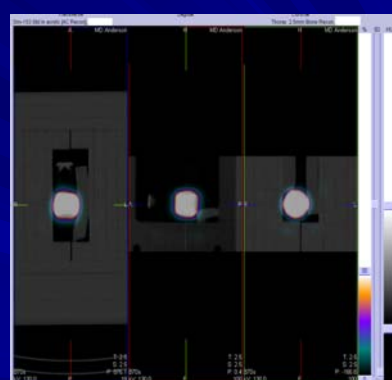
<u>Cts/uCi</u>

C_{std} = SPECT Cts in std VOI

(30% threshold)

A_{std} = uCi in std

$S = C_{std} / A_{std}$



Sm-153 EDTMP SPECT/CT

Tumor absolute activity (FIA) versus Time

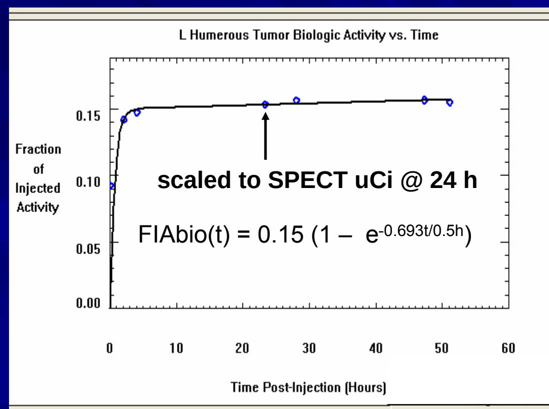
uCi @ 24 h

C_{tumor} = SPECT Cts in VOI

C_{std} = SPECT Cts in std VOI

A_{std} = uCi in std

$$A_{tumor} = \frac{C_{tumor} \times A_{std}}{C_{std}}$$



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

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 (GBq) = 71.6

Residence Time (T) = 10.7 h

Dose (E × A × T / M)= 172 Gy

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