SPECT/CT: Basics, Quality Assurance, and Clinical Applications

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Educational Objectives

1. To understand the physics principles underlying SPECT/CT image acquisition and reconstruction
2. To understand the quality assurance procedures specific to SPECT/CT systems
3. To become familiar with clinical applications of SPECT/CT imaging

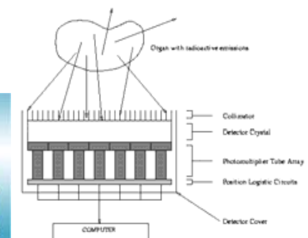
SPECT

- Single Photon Emission Computed Tomography
  - Radio-pharmaceutical administration – injected, ingested, or inhaled
  - Bio-distribution of pharmaceutical – uptake time
  - Decay of radionuclide from within the patient – the source of information
  - SPECT – Gamma camera detects radionuclide emission photons
  - PET – Coincidence ring detector detects annihilation photons
  - Tomography performed to image the radio-pharmaceutical distribution within the patient
- Used for visualization of functional information based on the specific radio-pharmaceutical uptake mechanism

Gamma Camera

- NaI(Tl) is the scintillator of choice
  - High light output and High detection efficiency (~85% at 140 keV for 3/8 in. NaI)
  - Good energy resolution (~10% at 140 keV)
  - Large crystals (50 cm x 40 cm)
  - Hygroscopic!





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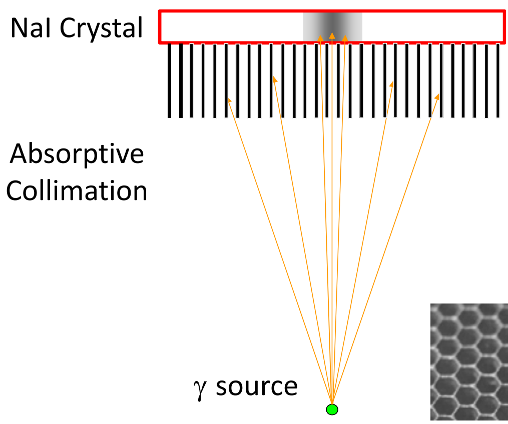
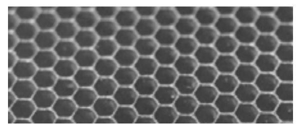
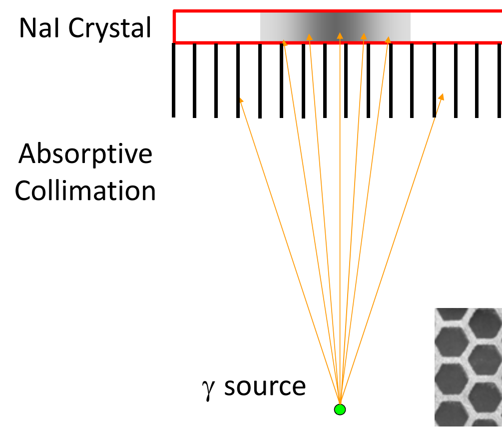
- Intrinsic Spatial and Energy Resolution
  - # of scintillation photons, $N \propto$ Gamma-ray energy, E
  - Spatial Resolution = $100 \times \sigma/N \propto 1/\sqrt{N} \propto 1/\sqrt{E}$
  - Energy Resolution = $100 \times FWHM/E \propto 1/\sqrt{E}$

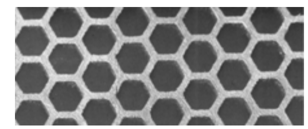
Collimators



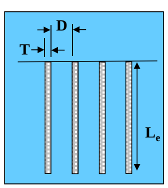


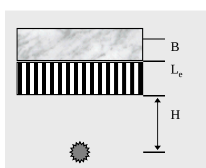
Collimators

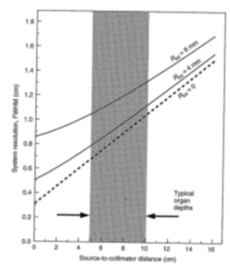




Collimator Resolution







Cherry, Sorenson, & Phelps, Physics of Nuclear Medicine, 2003

Collimator Resolution $R_g = \dfrac{D(L_e + H + B)}{L_e}$

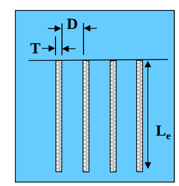
System Resolution $R_s^2 = R_i^2 + R_g^2$

Resolution is highest closest to the collimator therefore while imaging position patients as close as possible to collimator face

Collimator Efficiency

$G = \theta F$ where $\theta = C(D/L_e)^2$

$G = \dfrac{CD^4}{L_e^2(D+T)^2}$



θ = fraction of 4π

F = exposed fraction

Parallel Hexagonal hole C =

LEHR = 1.3×10^{-4}

MELP = 3.1×10^{-4}

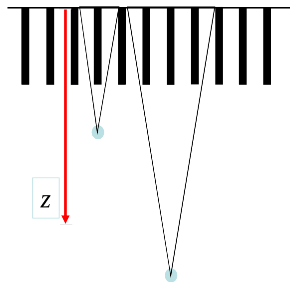
BiCoreTM Collimators Specifications

Collimators	LEHS Low Energy High Sensitivity	LEAP Low Energy All Purpose	LEHR Low Energy High Resolution	LEUHR Low Energy Ultra High Resolution	LEFB Low Energy Fan Beam	MELP Medium Energy Low Penetration	HE High Energy	UHE Ultra High Energy
Isotope	^{99m}Tc	^{99m}Tc	^{99m}Tc	^{99m}Tc	^{99m}Tc	^{67}Ga	^{131}I	^{18}F
Hole Shape	Hex	Hex	Hex	Hex	Hex	Hex	Hex	Hex
Number of Holes (x1000)	28	90	148	146	64	14	8	4
Hole Length (mm)	24.05	24.05	24.05	35.8	35	40.64	59.7	50.5
Septal Thickness (mm)	0.36	0.2	0.16	0.13	0.16	1.14	2	3.4
Hole Diameter (mm across the flats)	2.54	1.45	1.11	1.16	1.53	2.94	4	2.5
Sensitivity @ 10 cm1 (cpm/_Ci)	1020	330	202	100	280	310	147	185
Geometric Resolution @ 10 cm (mm)	14.6	8.3	6.4	4.6	6.3	10.8	13.2	10.6
System Resolution @ 10 cm1 (mm)	15.6	9.4	7.4	6.0	7.3	12.5	13.4	19.0
Septal Penetration (%)	1.5	1.9	1.5	0.8	1.0	1.2	3.5	3.4
Focal Length @ Exit Surface (mm)	n.a.	n.a.	n.a.	n.a.	445	n.a.	n.a.	n.a.
Weight (lb)	42	49	45	56	67	136	296	260
Weight (kg)	18.9	22.1	20.4	25.2	30.5	61.8	134.5	117.0

1. Values measured in accordance with NEMA Standards Publication NU-1 2001 using 3/8" crystal.

Sensitivity versus Source Distance

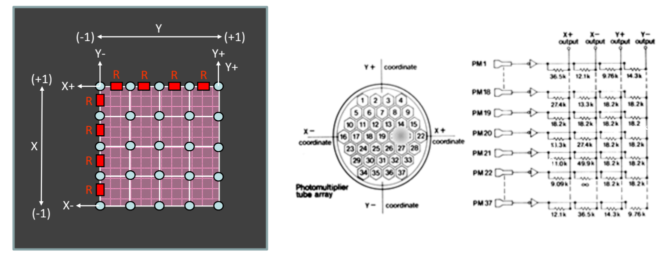
- Sensitivity: the detected photons count rate per unit activity [cps/uCi]
- Photon flux vs. distance $\propto z^{-2}$
- Crystal area vs. distance $\propto z^{2}$
- Overall sensitivity $S \propto z^{-2} \times z^{2} \sim$ constant



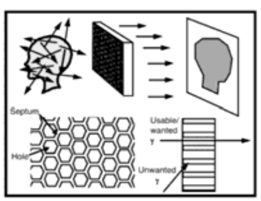
$$z = L_e + H + B$$

Anger Logic for Event Position

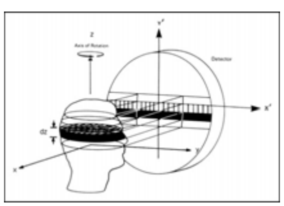
- Interaction location based on relative signal between X^+ and X^- (for X location) & Y^+ and Y^- (for Y location)
  - $X = (X^+ - X^-)/(X^+ + X^-)$ → range -1 to +1
  - $Y = (Y^+ - Y^-)/(Y^+ + Y^-)$ → range -1 to +1
- Interaction Energy $\propto$ Total Signal = $X^+ + X^- + Y^+ + Y^-$



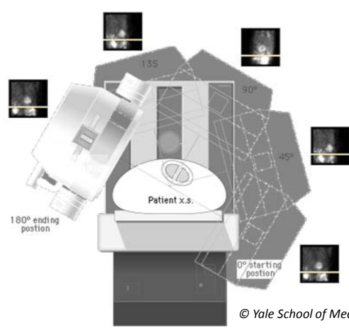
SPECT Acquisitions



Wernick & Aarsvold, Emission Tomography, 2004



SPECT in the year 2000, JNMT 24:233, 2000



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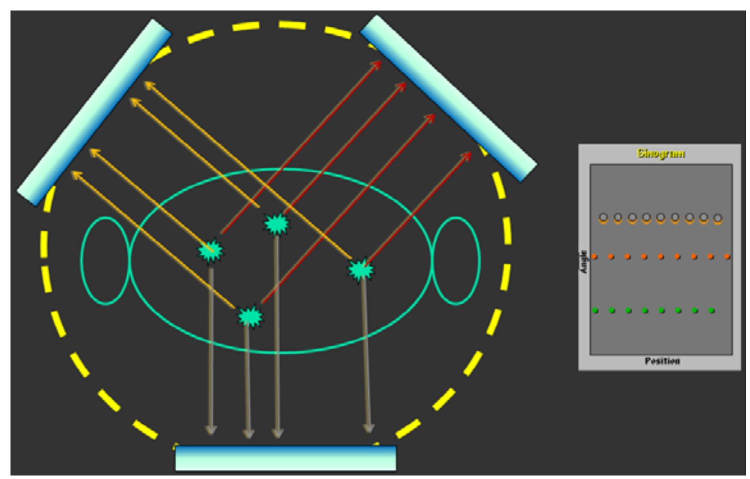
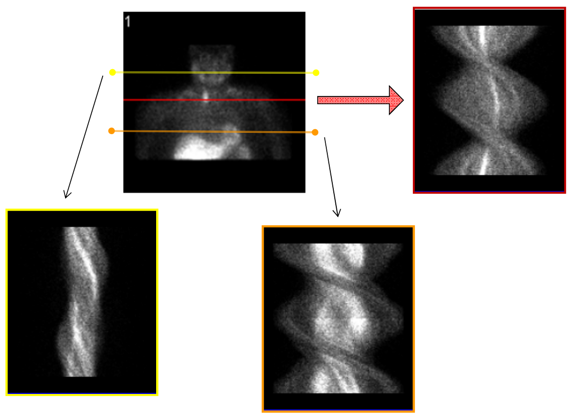
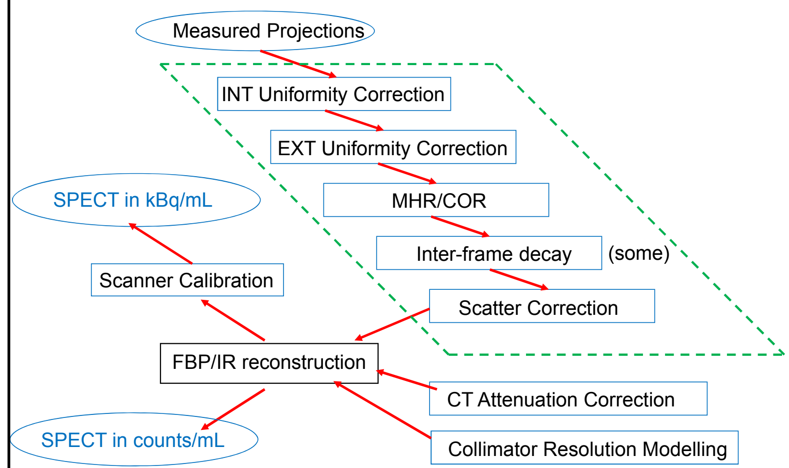
SPECT acquires 2D projections of a 3D volume



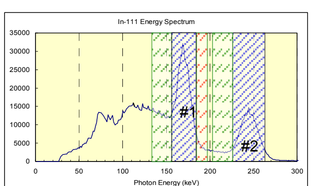


SPECT data corrections



SPECT Iterative Recon: Scatter Modeling

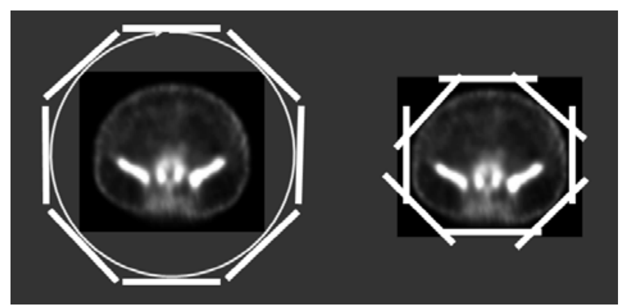
- Scatter compensation occurs before attenuation
  - the photopeak window contains scatter
  - attenuation accounts for the removal of photopeak photons
- Adjacent energy window based estimate (DEW and TEW): Scatter estimated as a weighted sum of adjacent energy window images, $Ci(x,y,\theta)$
  $S(x,y,\theta) = \Sigma_i\, k_i \times C_i(x,y,\theta)$
- Subtract scatter prior to reconstruction
  $P_{corr}(x,y,\theta) \rightarrow P(x,y,\theta) - S(x,y,\theta)$
- Incorporate scatter into forward projection
  $P(x,y,\theta) \rightarrow P_{corr}(x,y,\theta) + S(x,y,\theta)$



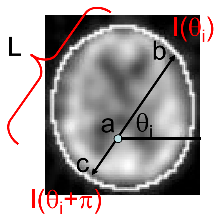
	Energy Window Definition		Energy Range	SF
TEW	Lower Scatter	15%	131 - 156	0.5
	Photopeak #1	172 keV w/ 15%	156 - 181	-
	Upper Scatter	8%	181 - 195	0.9375
DEW	Lower Scatter	10%	201 - 225	0.75
	Photopeak #2	247 keV w/ 15%	225 - 262	-

SPECT Acquisition Schema

- Circular versus (non-circular) body-contour orbit
- Step-and-Shoot versus Continuous Mode



SPECT violates Radon transform angular symmetry
→ Differential Attenuation



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

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

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

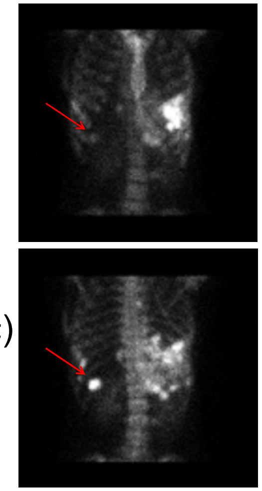
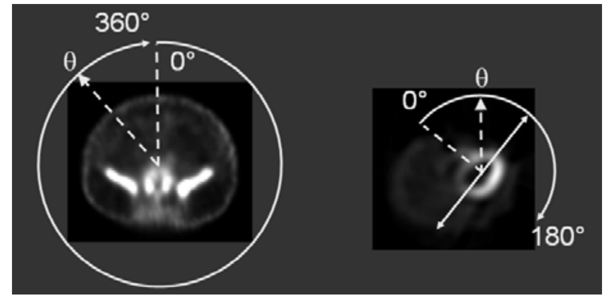


Image courtesy Bill Erwin

- Other mediating factors:
  - distance-dependent resolution
  - depth-dependent scatter

SPECT Acquisition Schema

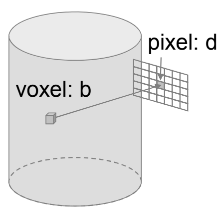
- SPECT projections acquired over 360-degrees
  - Exception: Cardiac SPECT acquired over 180°



SPECT Iterative Reconstruction

Maximum Likelihood Expectation Maximization (ML-EM)
Ordered Subset Expectation Maximization (OS-EM)

- Accounts for the statistical nature of photon detection
- Incorporates the system response p(b,d) – the probability that a photon emitted from an object voxel *b* is detected by projection pixel *d*
- p(b,d) captures…
  1. Depth-dependent resolution
  2. Position-dependent scatter
  3. Depth-dependent attenuation



$$a_{i,j,k} = a^{AC}_{i,j,k} \times a^{collimator}_{i,j,k} \times a^{efficiency}_{i}$$

- Use a measured attenuation map along with models of scatter and camera resolution to perform a far more accurate reconstruction

SPECT Iterative Reconstruction

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

Forward Projection

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

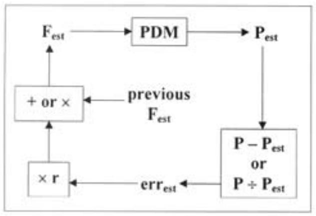
- True voxel intensity = sum of true detector intensities weighted by detection probabilities

Back Projection

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

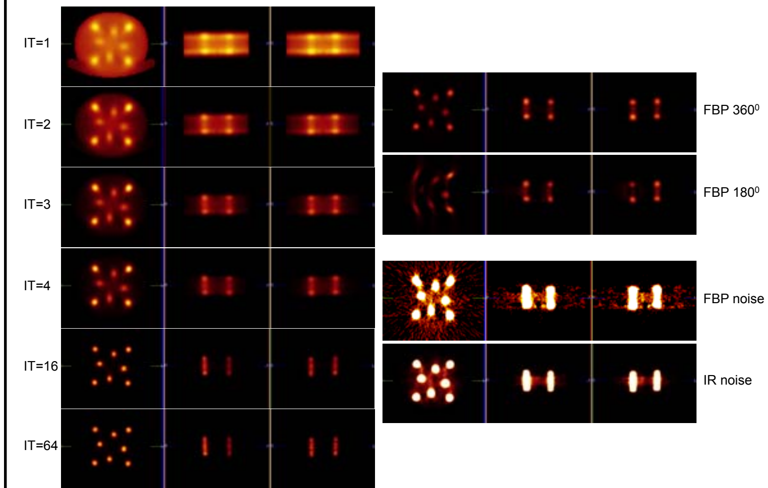
Iterative Reconstruction Flow Diagram

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



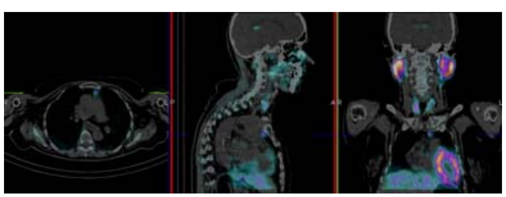
In clinical practice, the stopping criteria is number of iterations (a time constraint) instead of a convergence criteria.

SPECT Reconstructions



Hybrid SPECT/CT Motivation

- X-ray transmission CT
  - Improved speed (< 1 min)
  - High-resolution anatomical images
  - Higher radiation dose
- Functional-anatomical overlay (image fusion)
  - Improve localization of uptake regions
  - Increase confidence in interpretation



HU-to-μ (CT-AC) Transforms

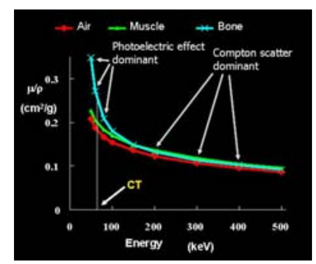
LaCroix et al., IEEE TNS 41, 1994

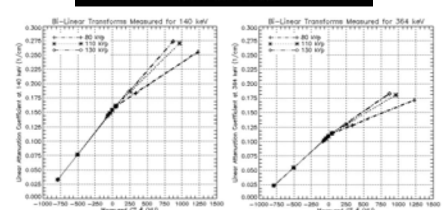
$$HU_x = \frac{\mu_x(E_{CT}) - \mu_w(E_{CT})}{\mu_w(E_{CT})} \times 1000$$

$$\mu_x(E_{CT}) = \left(1 + \frac{HU_x}{1000}\right) \times \mu_w(E_{CT})$$

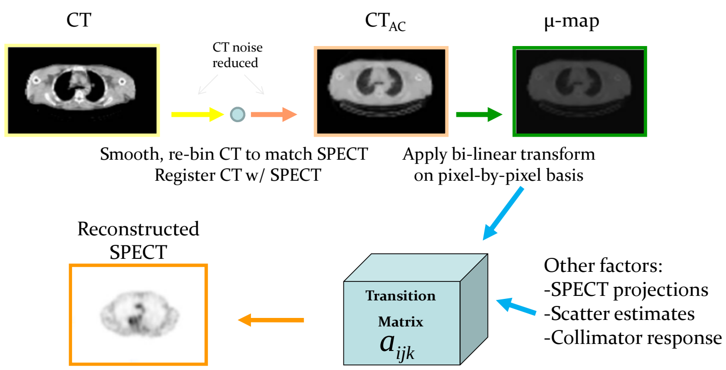
$$\mu_x(E) = \left(1 + \frac{HU_x}{1000}\right) \times \mu_w(E) \times \overbrace{\left(\frac{\mu_w(E_{CT})}{\mu_x(E_{CT})} \times \frac{\mu_x(E)}{\mu_w(E)}\right)}^{K}$$

- Photon energies different between CT and SPECT
- K≈1 for Compton Scatter dominates low Z at ECT (low HU)
- K≠1 for Photoelectric pertinent for high Z at ECT (high HU)
- HU-to-μ transform is piece-wise linear (bi- or tri-modal)

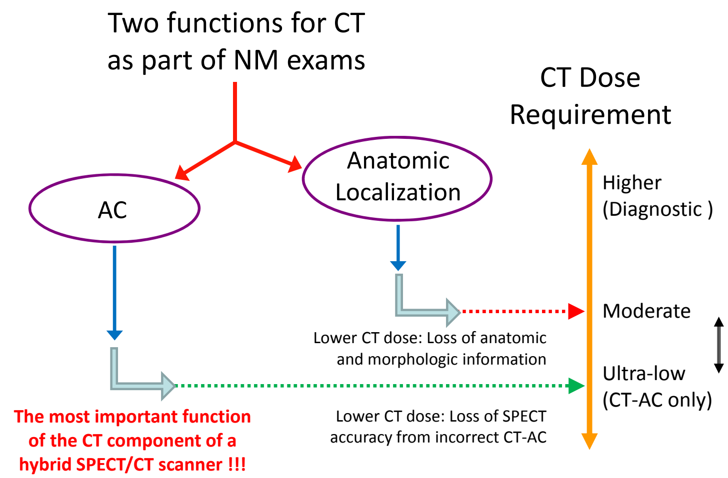




CT-based AC for SPECT/CT



Role of CT in SPECT/CT



SPECT/CT Quality Control

- Planar (AAPM Reports 6 and 9; NEMA NU 1-1994)
  - Energy resolution (Intrinsic)
  - Spatial resolution (Intrinsic and Extrinsic)
  - Uniformity (Integral and Differential)
  - Deadtime
  - Sensitivity (∀ collimator)
  - Pixel Size
  - Rotational Uniformity and Sensitivity Variation
  - Opposed-Head Spatial Registration
  - Multiple Energy-Window Spatial Registration
- SPECT (AAPM Reports 22 and 52)
  - Uniformity and Contrast (Image Quality)
  - Resolution
  - MHR/COR (∀ collimator)
- SPECT/CT (AAPM TG 177: Jim Halama)
  - SPECT and CT image registration
  - Image Quality (attenuation, scatter correction, iterative reconstruction)

SPECT/CT: Image Registration

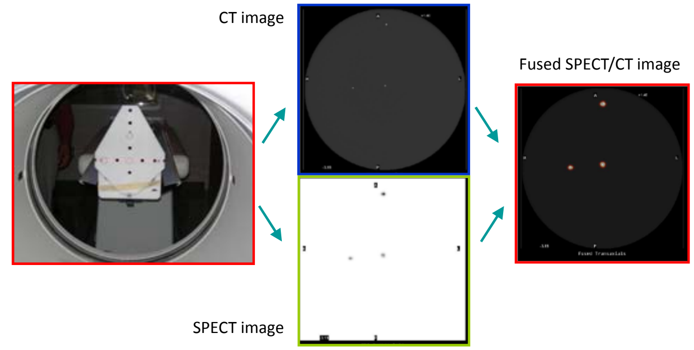
- To verify the electro-mechanical registration of the isocenter and reconstructed field-of-view between the SPECT and CT images
  - Does location (x, y, z) in SPECT image space spatially corresponds to location (x, y, z) in CT image space?
- SPECT/CT image registration is critical for
  - Accurate SPECT images via CT-based attenuation correction
  - Display of fused images for clinical interpretation
- Does <u>not</u> address mis-registration due to patient movement between SPECT and CT

Registration Test Setup A

- Acquire SPECT/CT scan of 3 point sources (capillary tubes) in air containing both CT-contrast and Tc-99m solution

Registration Test Setup A

- Acquire SPECT/CT scan of 3 point sources (capillary tubes) in air containing both CT-contrast and Tc-99m solution



Registration Test Setup B

- Use Co-57 button sources w/ SPECT Jaszczak phantom containing Tc-99m water
  - Co-57 emits 122 keV; Photopeak window 122 keV w/ 20% window
  - Tc-99m emits 140 keV; Photopeak window 140 keV w/ 15% window
- 19% of counts in ^{57}Co energy window (110-134 keV) contained in ^{99m}Tc energy window (129-150 keV)

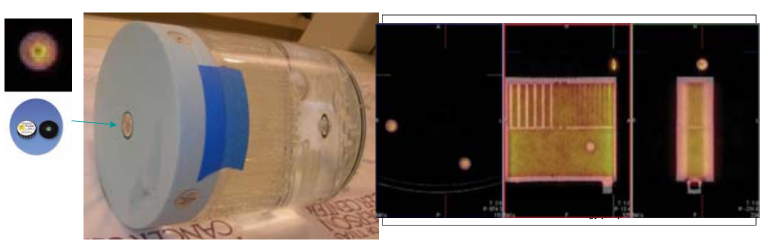
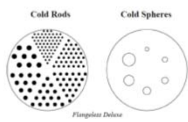


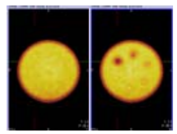
Image Registration – Data Analysis

- Overlay re-sampled SPECT and CT images in fused display
- For each of the 3 points determine the shift in (Δx, Δy, Δz) to match center of point source between SPECT and CT images
- Calculate the mean deviation between SPECT and CT images along any one direction as
  - Mean deviation along x-axis = $(\Delta x_1 + \Delta x_2 + \Delta x_3)/3$
  - Similar for y and z
- PASS criteria specifications TBD
  - Mean deviation along any axis is less than one SPECT-pixel used in routine clinical imaging

SPECT/CT: Image Quality

- ACR SPECT phantom (“Jaszczak”) with cold spheres and cold wedge section
- SPECT data acquisition based on ACR or AAPM Rpt 52
- Use typical CT exam parameters used for SPECT/CT scans
- Reconstruct the SPECT data with iterative reconstruction using CT-based AC, DEW scatter correction, and other routinely used reconstruction parameters
- Establish the baseline for image quality at Acceptance Test
- Evaluate the annual test results against baseline values



Clinical SPECT/CT Imaging

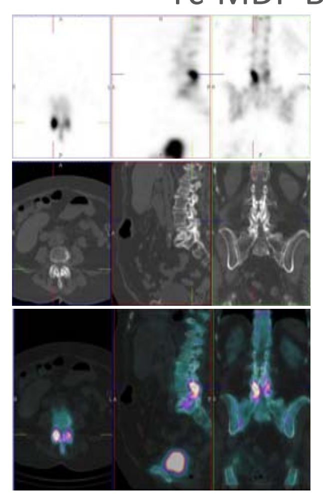
- Radiopharmaceuticals available for SPECT/CT imaging
  - Stress/Rest Myocardial Perfusion Imaging
    - Stress: ^{99m}Tc-sestaMIBI or ^{99m}Tc-Tetrafosmin
    - Rest: ^{99m}Tc-labeled agents or ^{201}Tl-chloride
  - ^{99m}Tc-MDP: bone diseases, bone metasteses
  - ^{99m}Tc-MAA: perfusion
  - ^{99m}Tc-sestaMIBI: parathyroid adenomas
  - ^{99m}Tc-sulphur colloid: liver/spleen, lymphoscintigraphy
  - ^{111}In-Pentetreotide: neuroendocrine cancers
  - ^{111}In-ProstaScint: prostate cancer
  - ^{123}I/^{131}I-MIBG: pheochromocytoma, neuroblastoma
  - ^{123}I/^{131}I-NaI: thyroid cancer
  - ^{99m}Tc-CEA: colorectal cancer
  - ^{99m}Tc-RBCs: hemangioma
  - ^{99m}Tc-HMPAO, -ECD: brain perfusion
  - ^{111}In-WBC: infection
  - ^{67}Ga-citrate: inflammation, lymphoma
  - ^{201}Tl-chloride: tumor perfusion
  - ^{153}Sm-EDTMP: skeletal disease
  - ^{89}SrCl: skeletal mets
- Some examples of clinical SPECT/CT imaging …

^{99m}Tc-MDP Bone Planar Scan

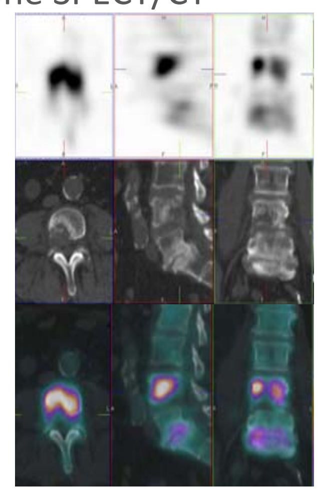
Focal uptake in the L4 lumbar spine: Metastases? Trauma? Inflammation?


Image courtesy Bill Erwin

^{99m}Tc-MDP Bone SPECT/CT



Degenerative joint disease (DJD)

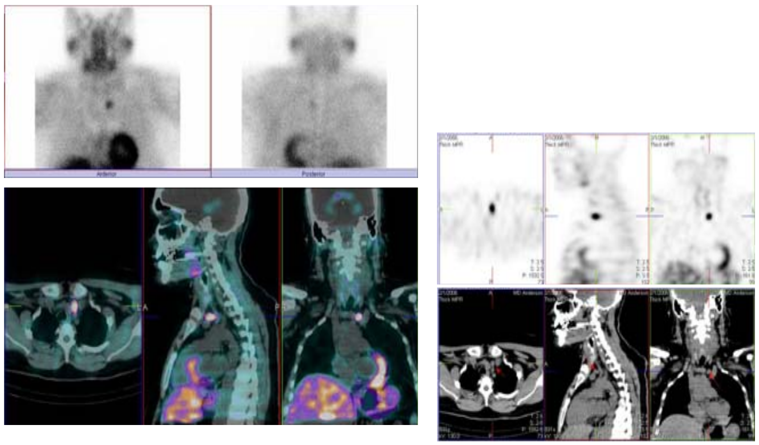


Bone metastases

Image courtesy Bill Erwin

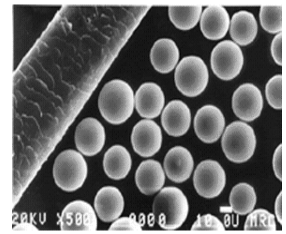
^{99m}Tc-sestaMIBI Parathyroid Imaging

Ectopic parathyroid adenoma: What is the exact location for surgery?



^{90}Y-microspheres Radioembolotherapy (Selective Internal RT)

- Hepatocellular Ca (TheraSphere®, MDS Nordion)
- Colorectal Ca liver mets (SIR-Spheres®, SirTex)



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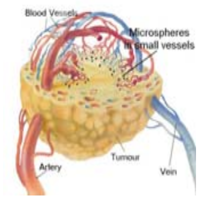
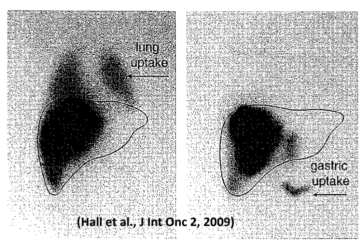


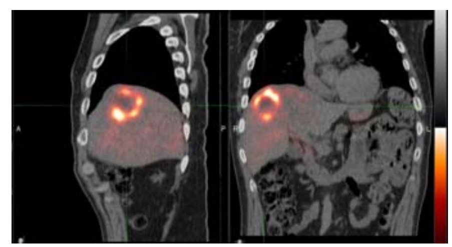
^{99m}Tc-MAA Pre-Therapy SPECT/CT

- ^{90}Y dose calculation & safety assessment
- ^{99m}Tc-MAA SPECT/CT
  - Catheter placement
  - Extra-hepatic shunting
  - Lung shunting
  - Perfusion



(Hall et al., J Int Onc 2, 2009)

99mTc-MAA SPECT/CT (~20 min)

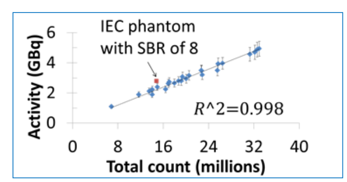


Detection of Extra-Hepatic MAA Shunting

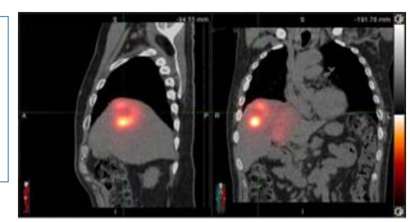
	Sensitivity	Specificity
Planar	32	98
SPECT	41	98
SPECT/CT	100	93

(Ahmadzadehfar et al, JNM, 2010)

90Y SPECT/CT (~35 min)

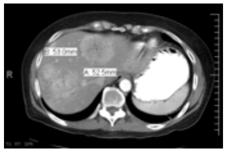


(Siman et al, JNM 56, 2015)

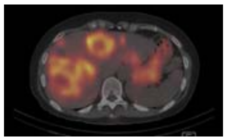


Pre and Post ^{90}Y-microsphere therapy

PRIOR

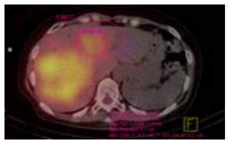


CT 3-June-2008



Tc-99m MAA SPECT/CT
24-June-2008

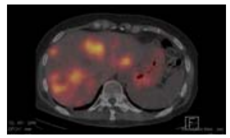
THERAPY



90Y SPECT/CT
2-July-2008

POST

CT 5-Sept-2008



Tc-99m MAA SPECT/CT
2-Sept-2008

^{99m}Tc-MAA Lung Perfusion SPECT/CT: Lung Function-based IMRT Planning

- **Goal**: lower radiation dose to functioning normal lung during IMRT of lung tumors by incorporating functional (in addition to anatomical) information in the treatment plan

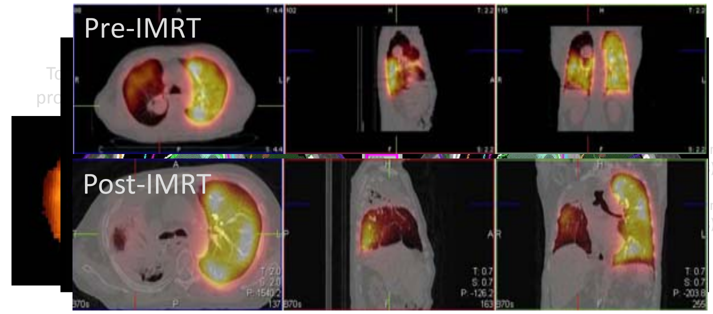
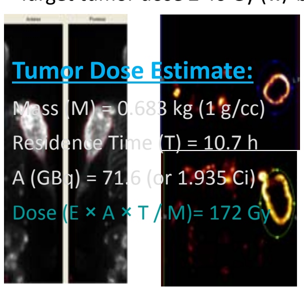
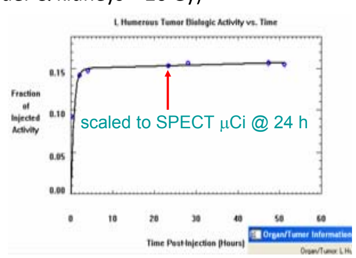


Image courtesy Bill Erwin

^{153}Sm-EDTMP Bone SPECT/CT: Internal Radionuclide Therapy

- Dosimetric imaging with 30 mCi tracer dose
  - Whole body planar images at 0, 2, 4, 24, 28, 48, and 52 hr
  - SPECT/CT of target tumor at 24 hr to estimate tumor volume and absolute uptake
  - Target tumor dose ≥ 40 Gy (w/ bladder & kidneys < 20 Gy)





Whole-body SPECT/CT

^{99m}Tc MDP Bone Imaging

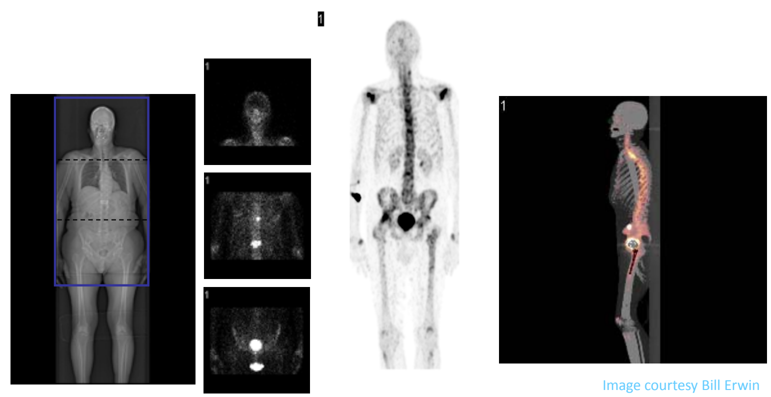
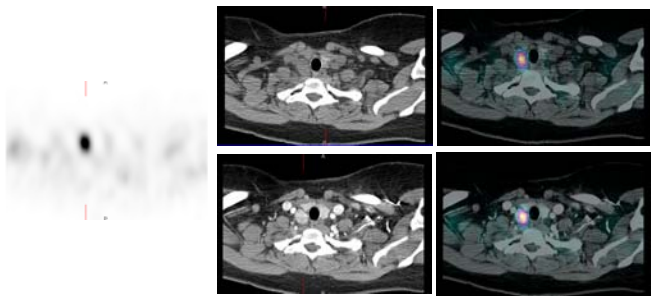


Image courtesy Bill Erwin

SPECT with contrast CT

- ^{99m}Tc Sestamibi SPECT/CT → Identification (NM)
- Multi-phase IV contrast H&N CT → Localization (Radiology)
- Synergy of SPECT/CT & contrast CT under clinical evaluation



Clinical Benefits of SPECT/CT

- Visualization, diagnosis and interpretation of primary and metastases diseases
  - Higher sensitivity and contrast than Planar imaging
  - CT scan increases confidence in interpretation of SPECT examination
- Surgical planning
- IMRT treatment planning
- ^{90}Y-microspheres therapy planning
- Internal radio-pharmaceutical therapy planning

SPECT/CT: Limitations

- Patient motion
  - Between SPECT and CT scans
  - Respiratory and cardiac motion during SPECT acquisitions
- Contrast CT
  - Contrast introduces electron density-material mismatch
    - μ map algorithms do not yet account for contrast CT
- Absolute quantification (Bq/mL) not yet fully developed
  - Radionuclide-dependent
  - Acquisition/reconstruction technique-dependent
  - Calibration techniques not yet standardized

‘Take-home’ message

Nuclear Medicine often referred to as
“uNclear” Medicine

so passé

SPECT/CT and PET/CT
has changed the paradigm to …

“New-clear” Medicine Imaging

– von Schulthess (MIB, 2004)