Quantitation in Nuclear Medicine

Michael King, Ph.D.

Department of Radiology, University of Massachusetts Medical School, Worcester, MA

e-mail: Michael.King@umassmed.edu

Outline of Talk

- Examples of Quantitation in Nuclear Medicine
- Factors That Impact Absolute Quantitation of Activity
- Correction for Attenuation
- Correction for Scatter
- Correction for Spatial Resolution
- Partial volume Effect
- Summary

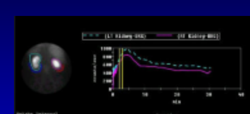
Examples of Quantitation in Nuclear Medicine?

- Physiological Function / Dynamic Behavior
  - Thyroid Uptake
  - Kidney Function
  - Quantification of Blood Flow
  - Compartmental Modeling
  - LV Ejection Fraction
- Database Relative Localization
  - Relative Cardiac Perfusion
  - Brain Metabolism
- Absolute Quantification of Activity
  - PET: SUV diagnosis and monitoring therapy
  - SPECT: Dosimeter for radionuclide based therapy

http://www.biodex.com/radio/thyroid/thyroid_140feat.htm

Examples of Quantitation in Nuclear Medicine?

- Physiological Function / Dynamic Behavior
  - Thyroid Uptake
  - Kidney Function
  - Quantification of Blood Flow
  - Compartmental Modeling
  - LV Ejection Fraction
- Database Relative Localization
  - Relative Cardiac Perfusion
  - Brain Metabolism
- Absolute Quantification of Activity
  - PET: SUV diagnosis and monitoring therapy
  - SPECT: Dosimeter for radionuclide based therapy



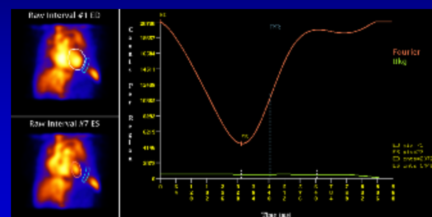
http://surge.ods.org/xeleris/mag3_renal.pdf

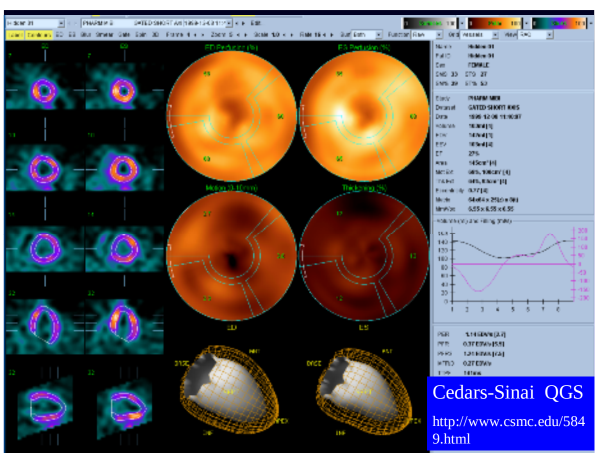
Examples of Quantitation in Nuclear Medicine?

- Physiological Function / Dynamic Behavior
  - Thyroid Uptake
  - Kidney Function
  - Quantification of Blood Flow
  - Compartmental Modeling
  - LV Ejection Fraction
- Database Relative Localization
  - Relative Cardiac Perfusion
  - Brain Metabolism
- Absolute Quantification of Activity
  - PET: SUV diagnosis and monitoring therapy
  - SPECT: Dosimeter for radionuclide based therapy

Cardiac LV Ejection Fraction

- $EF = [(Vol\ LV_{ED}) - (Vol\ LV_{ES})] / (Vol\ LV_{ED})$
- Sensitive parameter for ventricular performance
- Started with planar Gated-Blood-Pool Studies where it is estimated based on counts within ROI with Bkg correction.



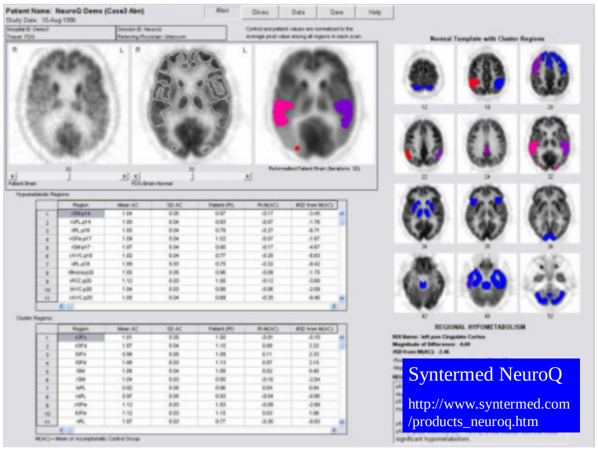


Cedars-Sinai QGS

http://www.csmc.edu/5849.html

Examples of Quantitation in Nuclear Medicine?

- Physiological Function / Dynamic Behavior
  - Thyroid Uptake
  - Kidney Function
  - Quantification of Blood Flow
  - Compartmental Modeling
  - LV Ejection Fraction
- Database Relative Localization
  - Relative Cardiac Perfusion
  - Brain Metabolism
- Absolute Quantification of Activity
  - PET: SUV diagnosis and monitoring therapy
  - SPECT: Dosimeter for radionuclide based therapy



Examples of Quantitation in Nuclear Medicine?

- Physiological Function / Dynamic Behavior
  - Thyroid Uptake
  - Kidney Function
  - Quantification of Blood Flow
  - Compartmental Modeling
  - LV Ejection Fraction
- Database Relative Localization
  - Relative Cardiac Perfusion
  - Brain Metabolism
- Absolute Quantification of Activity
  - PET: SUV diagnosis and monitoring therapy
  - SPECT: Dosimeter for radionuclide based therapy

Determination of SUV in PET

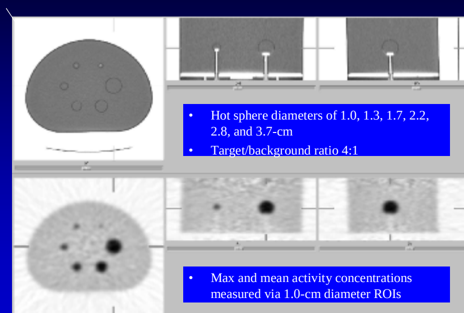
- Standardized Uptake Value (SUV)

$$\text{SUV} = \frac{\text{(decay corrected activity/ml of lesion)}}{\text{(injected activity / patient weight in g)}}$$

- Patient Compliance
  - fasting, blood glucose levels
- Scan Conditions
  - time post-injection, patient motion, CT AC
- System Performance
  - calibration, QA, performance characteristics of the system, reconstruction algorithm, ROI type

Adapted from Osama Mawlawi, “Factors affecting accurate quantification in PET/CT”, AAPM Summer School, 2008

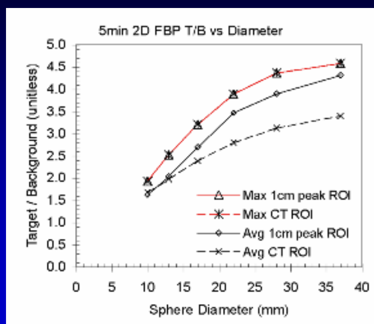
Size-Dependent Resolution Losses (PVE)



Modified NEMA NU-2 IQ Phantom

Paul Kinahan, SNM 2008

Effect of ROI Definition



Paul Kinahan, SNM 2008

Need for Quantification of Absolute Activity For Therapy Applications in SPECT

- Pretreatment tracer imaging to predict the absorbed dose during therapy (treatment planning)
- Post-therapy imaging
  - Monitoring radiation dose during therapy
  - To establish correlation between dose-response/toxicity
- Dr. Sgouros will discuss Radionuclide Therapy and Dosimetry – I will focus on factors impacting quantification of activity.

Adapted from Yuni Dewaraja, SNM 2008

Absolute Quantitation of Activity in SPECT (and PET)

- A(Bq) = R(cps) / [n (photons/dis) x D(c/photon)]
- A = Tissue Activity in dps or Bequerel (Bq)
- R = Count Rate in cps from structure of interest as determined by imaging
- n = Fractional Emission Rate of photons of given energy
- D = Detection Efficiency of imaging system for given energy photons
- Problem is correcting for **Detection Efficiency** for structure of interest **inside** the patient.

SPECT Detection Efficiency Depends On

- Imaging System Dependent
  - Collimator efficiency
  - Crystal detection efficiency and energy window fraction
  - System spatial resolution and septal penetration
  - Crosstalk between energy windows, backscatter, lead x-rays
  - Counting rate losses
- Patient Dependent
  - Photon attenuation
  - Detection of scattered photons
  - Kinetics of radiopharmaceutical during imaging
  - Patient motion
- Processing Dependent
  - Reconstruction algorithm and parameters
  - ROI definition
- Research related to improving quantification with SPECT

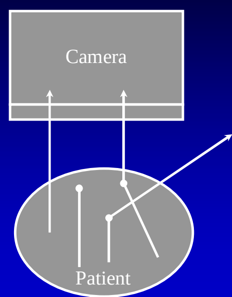
Attenuation and Scatter

- Emitted photons can be transmitted, absorbed, or scattered.
- Attenuation (absorption and scattering) removes counts.

  $I = I_0 \exp(-\mu x)$ Good Geometry
- Count loss depends on μ of material and x of source.
- Scattering adds back counts.

  $I = B(\mu x) I_0 \exp(-\mu x)$ Broad Beam

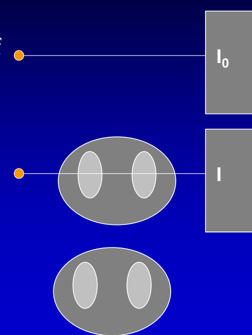
  B = Buildup Factor = (P + S) / P
- Need to account for BOTH for correct quantitation



SPECT Correction for Attenuation: Estimation of Attenuation Maps

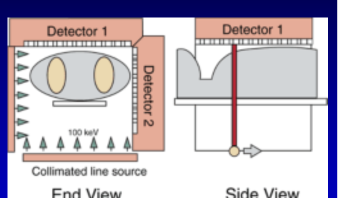
- To correct for attenuation need a patient specific map of how μ varies within slices.
- Acquire "Blank Scan" to obtain unattenuated intensity (I_0).
- Measure attenuation profile when patient is present (I).
- Divide and transform

  $\mu = [\ln (I_0/I)]/x$
- Reconstruct attenuation maps with FBP or iterative reconstruction method.



Estimation of Attenuation Map: Scanning Line Source

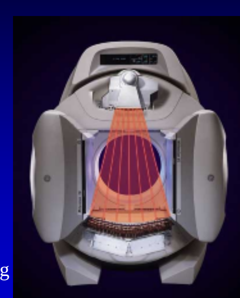
- Tan, JNM 34:1752-60, 1993
- Electronic windowing of imaging reduces cross-talk between emission and transmission windows
- Gd-153 line source
- Photon energies 97 and 103 keV
- 242 day half-life
- Method used at one point by 3 major manufacturers



http://www.medical.philips.com/main/products/nuclearmedicine/products/vantage_pro.html

Estimation of Attenuation Maps: Combined Emission and CT imaging

- Hasegawa, Proc SPIE 1231: 50-60, 1990.
- CT shares patient bed
- No cross-talk (x-ray intensity much greater than emission)
- Low noise
- CT anatomy for defining ROI
- Convert X-ray to Emission attenuation map
- Patient respiration and motion between CT and emission imaging
- Added radiation dose of CT



http://apps.gemedicalsystems.com/geCommunity/nmpet/hawkeye/hawkeye_presentation.jsp

Iterative Reconstruction and Inclusion of Attenuation Correction

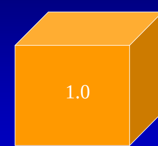
$$\text{Slice}^{NEW} = \text{Slice}^{OLD} \text{ x Norm Backproj } \left(\frac{\text{Measured Data}}{\text{Proj Slice}^{OLD}} \right)$$

Iterative Reconstruction and Inclusion of Attenuation Correction

$$\text{Slice}^{NEW} = \text{Slice}^{OLD} \text{ x Norm Backproj } \left(\frac{\text{Measured Data}}{\text{Proj Slice}^{OLD}} \right)$$

STEPS

1. Initial guess as to voxel counts – typically all 1.0's



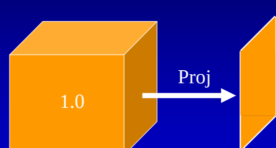
3D Stack of Slice^{OLD} Estimates

Iterative Reconstruction and Inclusion of Attenuation Correction

$$\text{Slice}^{NEW} = \text{Slice}^{OLD} \text{ x Norm Backproj } \left(\frac{\text{Measured Data}}{\text{Proj Slice}^{OLD}} \right)$$

STEPS

1. Initial guess as to voxel counts – typically all 1.0's
2. Make set of projections – one for each angle data acquired



3D Stack of Slice^{OLD} Estimates

2D Project of Slice^{OLD}

Iterative Reconstruction and Inclusion of Attenuation Correction

$$\text{Slice}^{NEW} = \text{Slice}^{OLD} \text{ x Norm Backproj } \left(\frac{\text{Measured Data}}{\text{Proj Slice}^{OLD}} \right)$$

STEPS

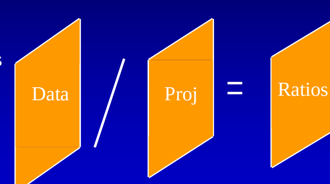
3. Do pixel by pixel division of projections into Measured Data to obtain Update Ratios

   If Ratio:

   > 1.0 Proj too small

   = 1.0 Proj just right

   < 1.0 Proj too big

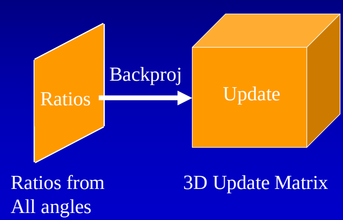


Iterative Reconstruction and Inclusion of Attenuation Correction

$$\text{Slice}^{NEW} = \text{Slice}^{OLD} \times \text{Norm Backproj}\left(\frac{\text{Measured Data}}{\text{Proj Slice}^{OLD}}\right)$$

STEPS

4. Backproject Ratios from ALL angles
5. Normalize (Divide by backprojection of all 1.0's)

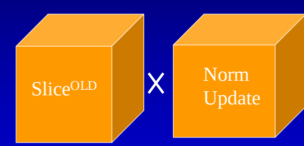


Iterative Reconstruction and Inclusion of Attenuation Correction

$$\text{Slice}^{NEW} = \text{Slice}^{OLD} \times \text{Norm Backproj}\left(\frac{\text{Measured Data}}{\text{Proj Slice}^{OLD}}\right)$$

STEPS

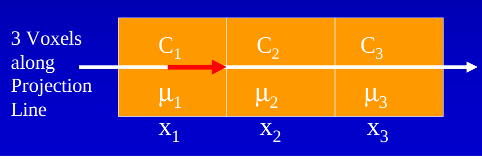
6. Voxel by voxel multiply Norm Update times Make set of projections – one for each angle data acquired
7. Repeat 2 to 6



Iterative Reconstruction and Inclusion of Attenuation Correction

Correction for Attenuation is done by modeling attenuation in the Projection and Backprojection operations.

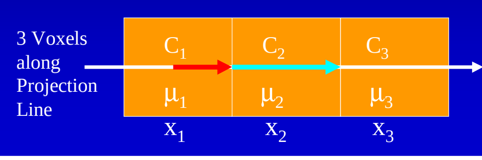
C_1 Contribution = $C_1 e^{-\mu_1 x_1/2}$



Iterative Reconstruction and Inclusion of Attenuation Correction

Correction for Attenuation is done by modeling attenuation in the Projection and Backprojection operations.

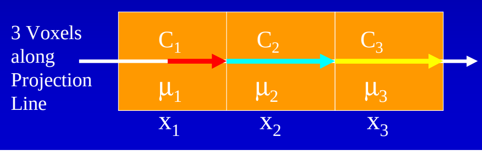
C_1 Contribution = $(C_1 e^{-\mu_1 x_1/2})\, e^{-\mu_2 x_2}$



Iterative Reconstruction and Inclusion of Attenuation Correction

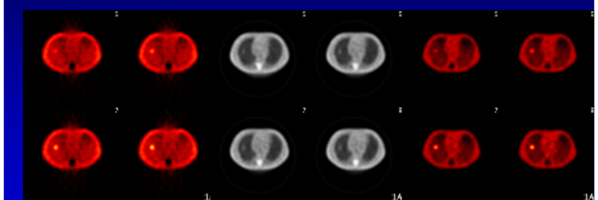
Correction for Attenuation is done by modeling attenuation in the Projection and Backprojection operations.

C_1 Contribution = $((C_1\, e^{-\mu_1 x_1/2})\, e^{-\mu_2 x_2})\, e^{-\mu_3 x_3}$



SPECT Correction for Attenuation: Attenuation Correction Algorithms

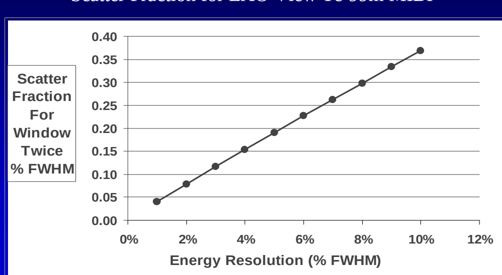
Tc-99m in Data Spectrum Anthropomorphic Phantom



FBP Attenuation Maps OSEM with AC

SPECT Correction for Scatter: Energy Resolution of Camera

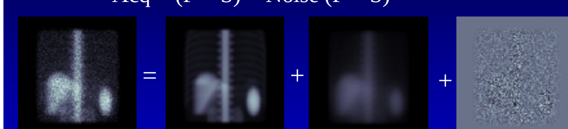
Scatter Fraction for LAO View Tc-99m MIBI



SPECT Correction for Scatter: Scatter Estimation Methods

Projection data can be written as:

Acq = (P + S) + Noise (P + S)



SPECT Scatter compensation attempts to reconstruct P

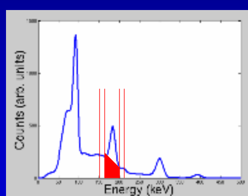
- Estimate S using Energy or Spatial Methods
- S can be subtracted before or used in reconstruction
- Note Noise

SPECT Correction for Scatter: Energy Spectrum Scatter Estimation

Use energy spectrum at each pixel to estimate scatter contribution at that pixel.

Example: Triple Energy Window (TEW)

Ogawa, IEEE TMI 10:408-412, 1991

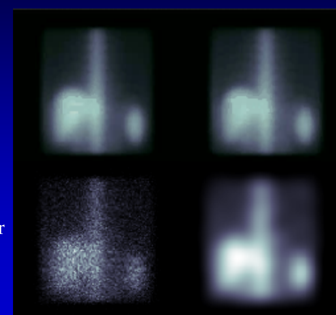


$$S' = .5W_2\left[\left(\frac{C_1}{W_1}\right) + \left(\frac{C_3}{W_3}\right)\right]$$

SPECT Correction for Scatter: Energy Spectrum Scatter Estimation

True noise free scatter projection

Noise free TEW scatter estimate



Noisy TEW scatter estimate

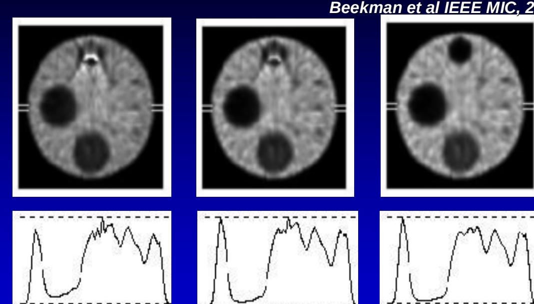
Filtered TEW scatter estimate

SPECT Monte Carlo Modeling of System Matrix

- Model imaging as $g = H f$ where:
  - g is projection vector (pixels)
  - f is source vector (voxels)
  - H is System Matrix (how voxels combined to give pixels)
- H is projection operator, and H^T is backprojection
- Use Monte Carlo (MC) to calculate H - problem SLOW
  - Floyd, JNM 27:1577-1585, 1986
- Fast Monte Carlo Reconstruction - 30 min on PC!
  - Beekman, IEEE MIC, 2001
  - Use Dual Matrix (MC for H, fast approximation for H^T)
  - Convolution Forced Detection

SPECT Monte Carlo Modeling of System Matrix

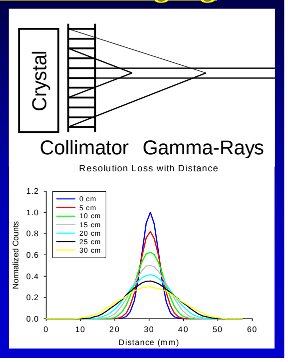
Beekman et al IEEE MIC, 2001



No scatter modeled | Approx. scatter PSF | MC-based 10^7 photons

Distance-Dependent Spatial Resolution in SPECT Imaging

- Resolution is combination of:
  - Intrinsic Resolution of Camera Head
  - Collimator Resolution
- System spatial resolution varies with distance from collimator

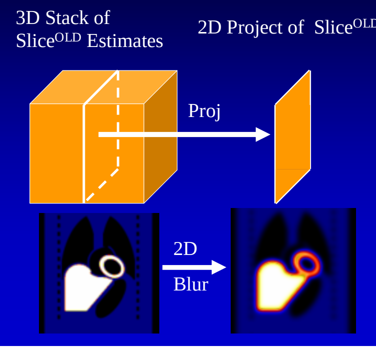


Iterative Reconstruction and Inclusion of Distance-Dependent Resolution

STEPS

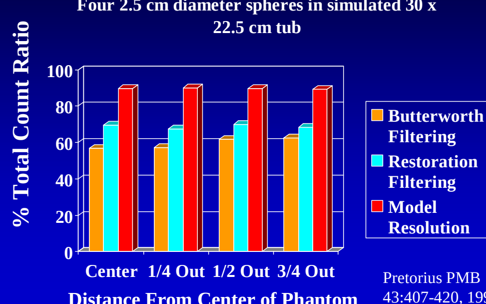
1. Select 2D plane
2. Blur matching distance from collimator
3. Weight for attenuation and add to Projection

NOTE: Smoothing improves resolution



Impact of Modeling Resolution in Reconstruction on Quantitation

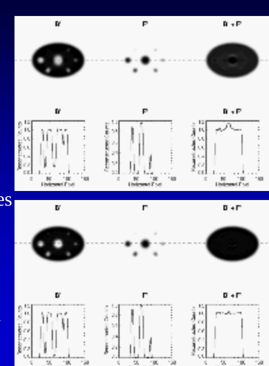
Four 2.5 cm diameter spheres in simulated 30 x 22.5 cm tub



Pretorius PMB 43:407-420, 1998

Partial Volume Effect (PVE)

- PVE is alteration in apparent concentration of activity due to spatial resolution.
- Template projection-reconstruction method of correction for the PVE (Da Silva JNM 42:772-9, 2001)
- Use CT to estimate templates.
- Create projections of the templates
- Reconstruct the projections to obtain correction factors at each voxel
- Convergence depends on distribution thus add perturbation of template to background (Du IEEE TMI 24:969976, 2005)

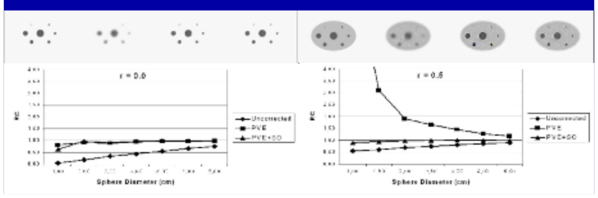


Partial Volume Effect

Example slices and plots of recovery coefficients (RC) for 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, and 6.0 cm diameter spheres for no background (r = 0.0), and background of 50% of sphere activity (r=0.5).

RC = 1.0 is ideal value

Boening IEEE TNS 53:1205-1212, 2006



SUMMARY

- Number of applications of quantitation in nuclear medicine.
- Quantitation is very important in PET to access the efficacy of new drugs and treatments.
- With accurate modeling of imaging in iterative reconstruction SPECT is quantitative.
  - Example: He & Frey, IEEE Trans. Med Imag 2008
- Validation of reconstruction and processing methods is crucial.
- If use standard reconstruction package from manufacturer, need to be sure reconstruction is quantitatively accurate.
  - Non-quantitative Ramp Filter in FBP

READ MORE ABOUT IT

- MJ Gelfand and SR Thomas: Effective use of Computers in Nuclear Medicine. McGraw-Hill, 1988.
- M N Wernick and J N Aarsvold: Emission Tomography: The Fundamentals of PET and SPECT. Elsevier Academic Press, 2004.
- H Zaidi: Quantitative Analysis in Nuclear Medicine Imaging. Springer, 2006.