PET/CT Attenuation Correction and Image Fusion

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Dilemma in PET Imaging

- When an area of abnormal tracer uptake is identified in a PET scan, physicians want to know:
- What is the anatomical location of the area?
- Is the uptake abnormal or physiological?
- If abnormal, what is the anatomical extent of the area and what is the recommended treatment plan?

Solution

- Compare the physiological PET images with anatomical CT images

Advantages of PET and CT

PET

- Uses metabolic imaging agent ^{18}F-FDG
- High sensitivity and specificity in many oncological applications

CT

- High contrast and spatial resolution
- Modality of choice for majority of anatomical imaging applications in oncology
  - Diagnosis and staging
  - RTP in radiation oncology
- Can be used for attenuation correction of PET data

Limitations of PET and CT

PET

- Lack of anatomical landmarks
- Limited spatial resolution (compared to CT)
- Physiologic tracer distributions must be identified

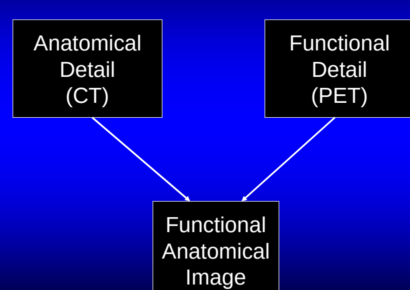
Advantages of CT

CT

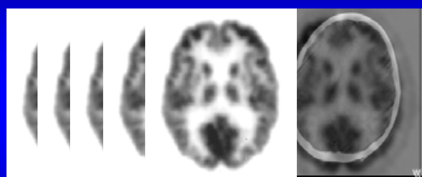
- Limited specificity
- Limited prognostic information
- Difficult to differentiate between post-treatment changes vs. recurrent tumor

Advantages of PET

Image Fusion



Overlay Images for Comparison

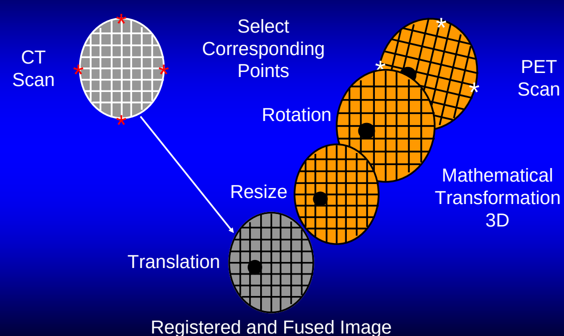


In order to fuse images, they first must be registered so that they can be compared on a pixel by pixel basis.

Traditional Methods

- Software Registration/Fusion
  - Rigid Body Transformations
    - Head
  - Non-rigid Body Transformations
    - Body

Traditional Methods (Rigid Body)



Problems

- Images are acquired:
  - With different modalities
  - At different times
  - With patient in different positions
  - With different pixel sizes
  - With different array sizes
  - With different slice thicknesses
- And organs move (heart, lungs, liver, GI tract)

Solution

- Develop an integrated system that acquires both anatomical and functional images during a single imaging session in a registered format, i.e. PET/CT.

Advantages of Integrated PET/CT

- Clinical CT and PET scans from a single imaging session with no patient movement
  - Accurate alignment of anatomy and function achieved by image registration during acquisition
- Rapid, low noise transmission scans for attenuation correction
- Anatomical geometry available to limit volume of PET reconstruction

PET/CT


PET Scanner

+


Multi-Slice CT Scanner

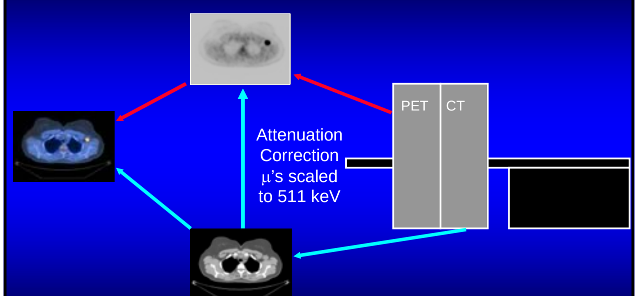
=


PET/CT Scanner

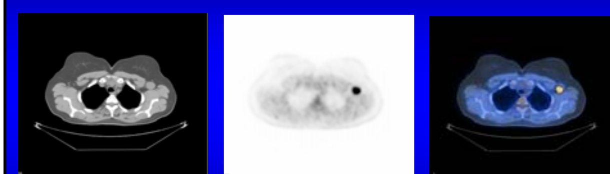
PET/CT System


PET Scanner CT Scanner

Functional Anatomical Mapping



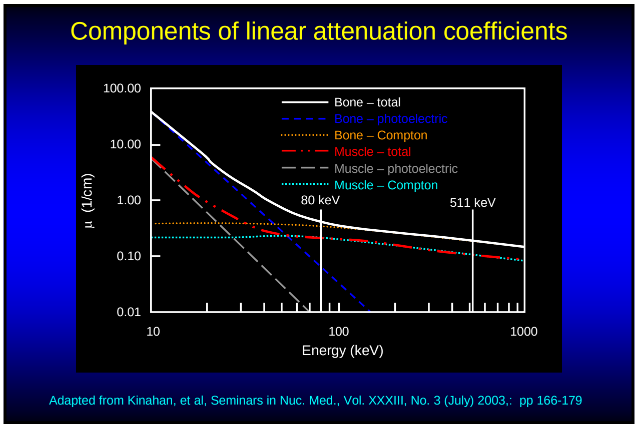
Breast Cancer

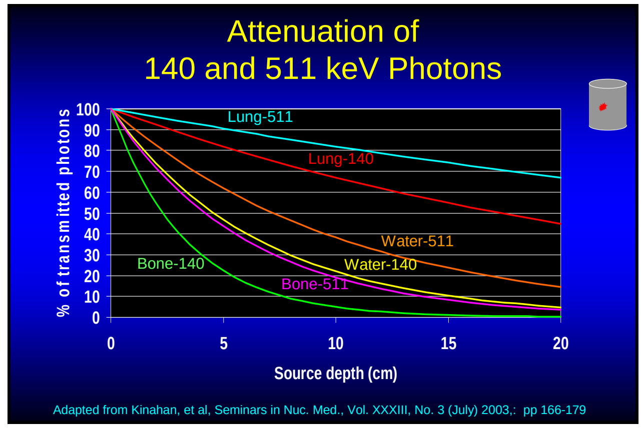

CT PET Fused Image

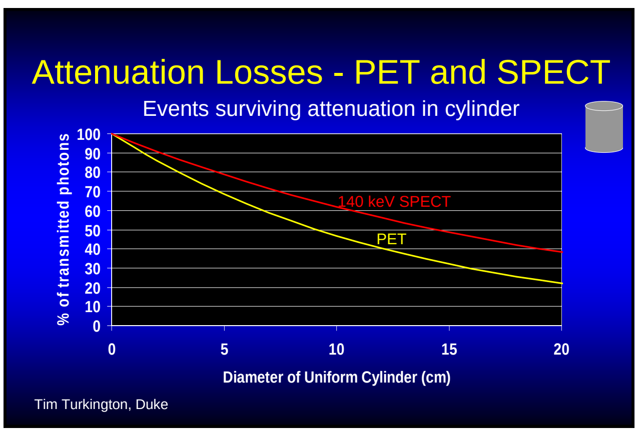
Purposes of PET/CT Integration

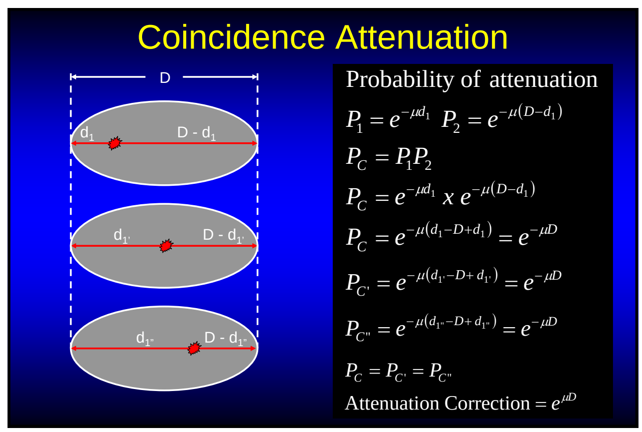
- Fuse the two sets of data to provide high quality anatomical correlations with radionuclide uptake
- Use the CT transmission data to correct for attenuation of PET data

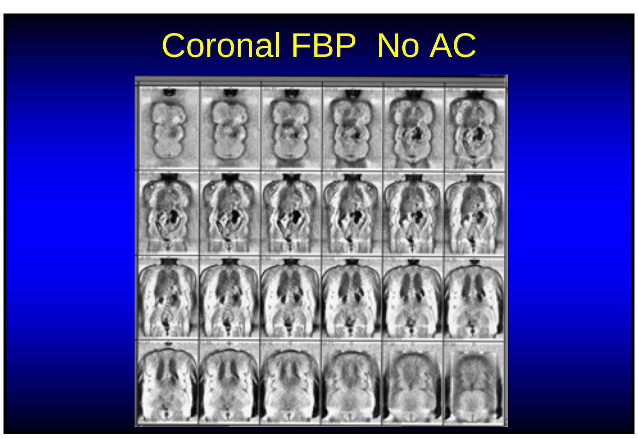
Attenuation Correction

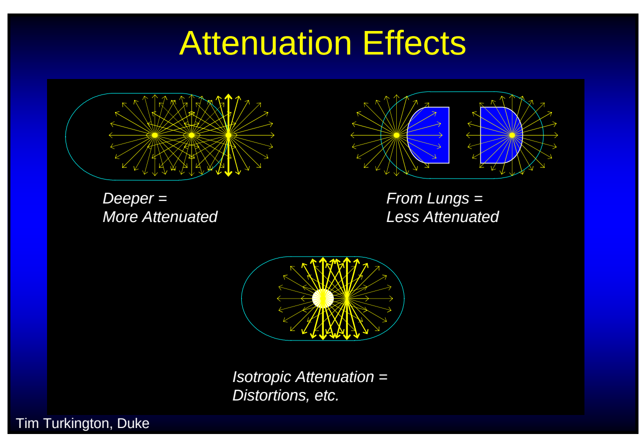

Components of linear attenuation coefficients
Bone – total
Bone – photoelectric
Bone – Compton
Muscle – total
Muscle – photoelectric
Muscle – Compton
80 keV
511 keV
μ (1/cm)
100.00
10.00
1.00
0.10
0.01
10
100
1000
Energy (keV)
Adapted from Kinahan, et al, Seminars in Nuc. Med., Vol. XXXIII, No. 3 (July) 2003,: pp 166-179

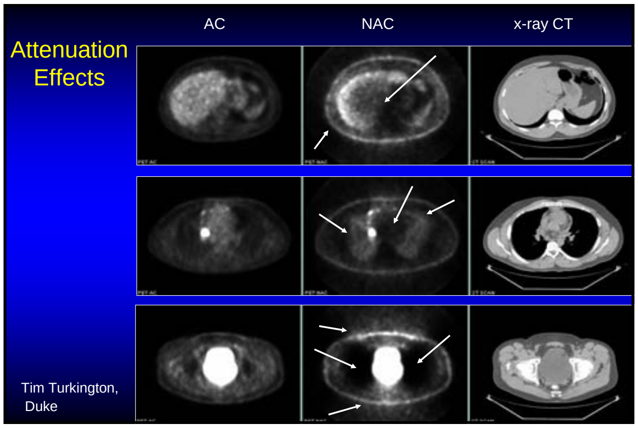

Attenuation of
140 and 511 keV Photons
% of transmitted photons
Lung-511
Lung-140
Water-511
Water-140
Bone-140
Bone-511
0
5
10
15
20
Source depth (cm)
Adapted from Kinahan, et al, Seminars in Nuc. Med., Vol. XXXIII, No. 3 (July) 2003,: pp 166-179

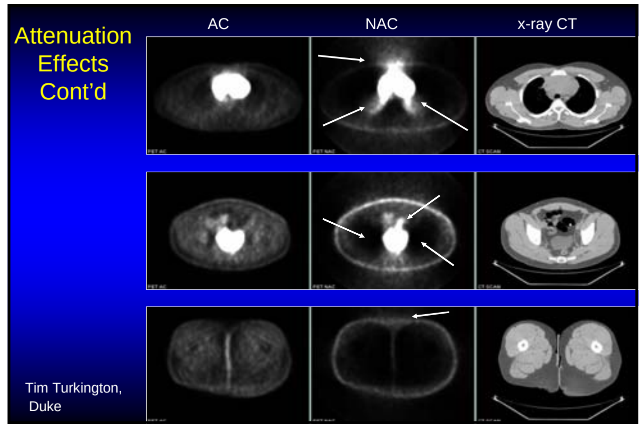

Attenuation Losses - PET and SPECT
Events surviving attenuation in cylinder
% of transmitted photons
140 keV SPECT
PET
Diameter of Uniform Cylinder (cm)
Tim Turkington, Duke

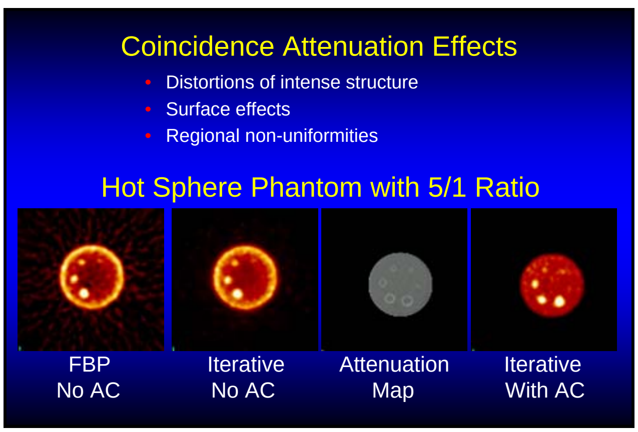

Coincidence Attenuation
D
d_1
D - d_1
$d_{1'}$
D - $d_{1'}$
$d_{1''}$
D - $d_{1''}$
Probability of attenuation
$P_1 = e^{-\mu d_1}$ $P_2 = e^{-\mu(D-d_1)}$
$P_C = P_1 P_2$
$P_C = e^{-\mu d_1} \; x \; e^{-\mu(D-d_1)}$
$P_C = e^{-\mu(d_1 - D + d_1)} = e^{-\mu D}$
$P_{C'} = e^{-\mu(d_{1'} - D + d_{1'})} = e^{-\mu D}$
$P_{C''} = e^{-\mu(d_{1''} - D + d_{1''})} = e^{-\mu D}$
$P_C = P_{C'} = P_{C''}$
Attenuation Correction = $e^{\mu D}$

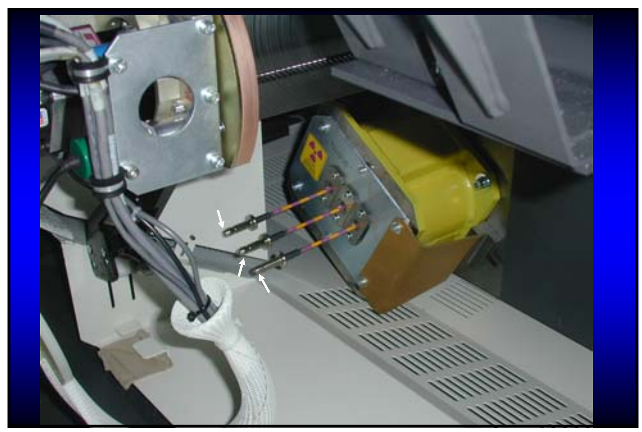

Coronal FBP No AC

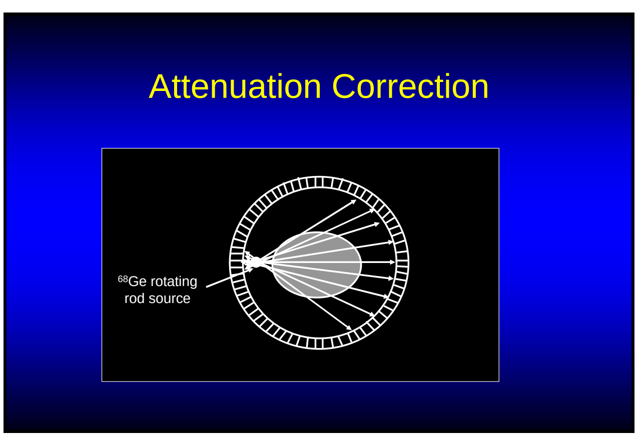

Attenuation Effects
Deeper =
More Attenuated
From Lungs =
Less Attenuated
Isotropic Attenuation =
Distortions, etc.
Tim Turkington, Duke

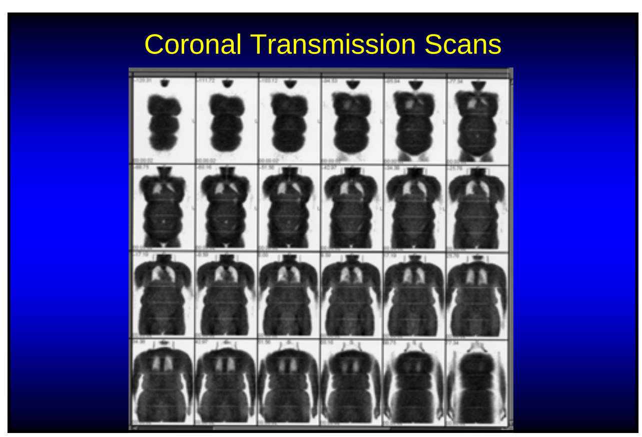

Attenuation Effects
AC
NAC
x-ray CT
Tim Turkington, Duke


Attenuation Effects Cont'd
AC
NAC
x-ray CT
Tim Turkington, Duke

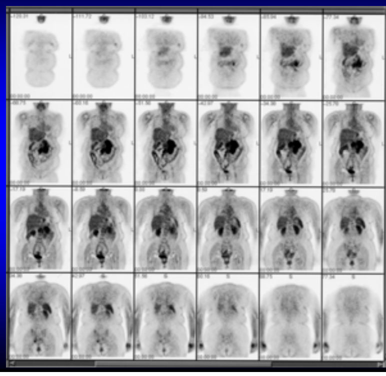

Coincidence Attenuation Effects
Distortions of intense structure
Surface effects
Regional non-uniformities
Hot Sphere Phantom with 5/1 Ratio
FBP No AC
Iterative No AC
Attenuation Map
Iterative With AC



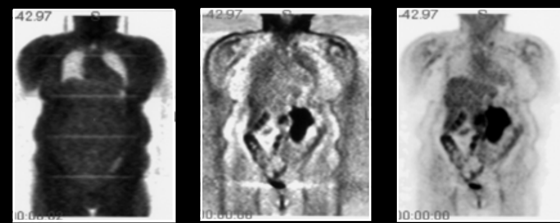

Attenuation Correction
68Ge rotating rod source


Coronal Transmission Scans

Coronal Iterative with AC



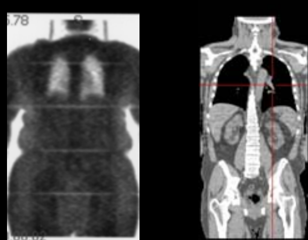
Attenuation Correction



Transmission Scan | Emission Scan w/o AC | Emission Scan with AC

Transmission Scan vs. CT Scan

Coronal View



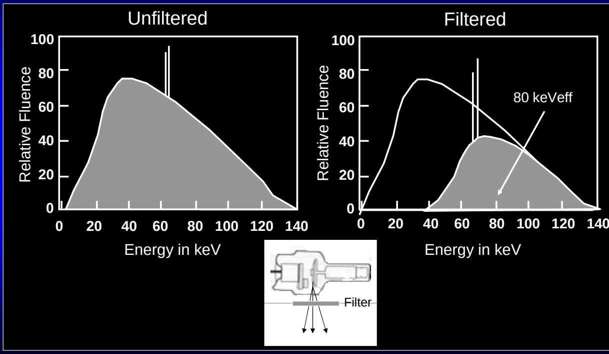
Transmission 511 keV | CT E_{eff} = 80 keV

Note! Different subjects

Advantages of CT Transmission Data

- Lower statistical noise than other techniques
- Significantly decreased acquisition time
- Post-injection scanning with negligible contamination from 511 keV photons
- Eliminates cost of transmission source hardware and periodic replacement of sources
- Anatomical information can be used in PET image reconstruction process

X-Ray Energy Spectrum



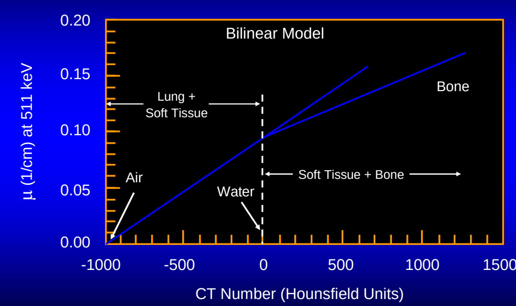
Question

How can we use a CT scan to perform attenuation correction of images acquired with single photon emitters?

CT# and Attenuation Coefficients

- CT# = Hounsfield Units
- CT#(material) = $1000 * \dfrac{(\mu_{material} - \mu_{water})}{(\mu_{water} - \mu_{air})}$
- The $\mu_{material}$ depends on:
  - Density and atomic number of material
  - Effective energy of X-ray beam
- CT#(water) = 0
- CT#(air) = -1000

Calibration Curve for Scaling of Attenuation Maps from X-ray CT Data



Adapted from Blankespoor, et al, IEEE Trans. Nuc. Sci., Vol. 43 pp 2263-2274, 1996.

Attenuation Correction at a Specific Energy (E keV)

- For CT# < 0, materials are assumed to have an energy dependence similar to water.

$$\mu_{material,E} = \frac{(\mu_{water,E} - \mu_{air,E}) * CT\#}{1000}$$

- CT# > 0 are treated as mixture of bone and water, and attenuation values are converted from measurements at the effective X-ray energy (keVeff) to values at the required energy (E).

$$\mu_{material,E} = \mu_{water,E} + \frac{CT\# * \mu_{water,keVeff} * (\mu_{bone,E} - \mu_{water,E})}{1000 * (\mu_{bone,keVeff} - \mu_{water,keVeff})}$$

→ Constants
→ From lookup table

Lookup Table

Energy in keV (E)	Isotope	$\mu_{air,E}$	$\mu_{water,E}$	$\mu_{bone,E}$
70	Tl-201	0.0002	0.1948	0.4974
93	Ga-67 (1)	0.0002	0.1753	0.3674
140	Tc-99m	0.0002	0.1545	0.2877
159	I-123	0.0002	0.1481	0.2681
171	In-111 (1)	0.0002	0.1448	0.2605
184	Ga-67 (2)	0.0002	0.1413	0.2523
245	In-111 (2)	0.0001	0.1287	0.2258
300	Ga-67 (3)	0.0001	0.1186	0.2059
364	I-131	0.0001	0.1106	0.1914
511	F-18	0.0001	0.0961	0.1655

Calibration Equations for Scaling of Attenuation Maps from X-ray CT Data

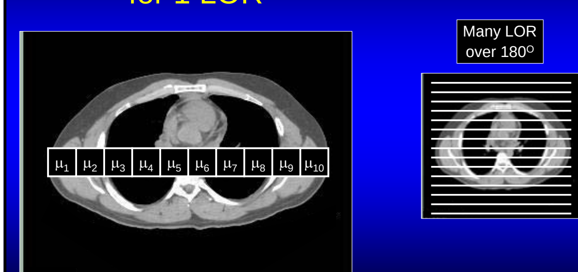
For CT# < 0

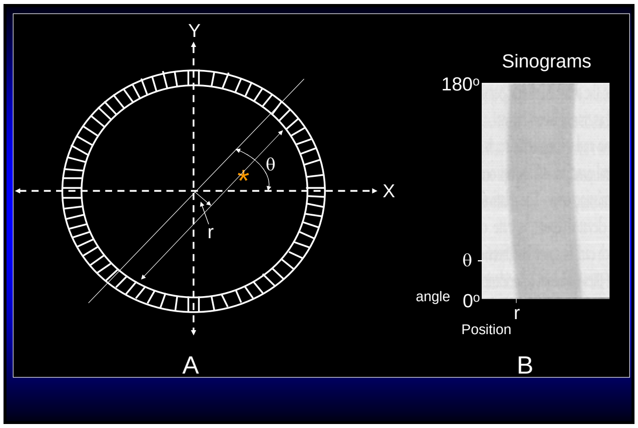
$$\mu_{511\ keV} = 9.60 \times 10^{-5}\ (CT\ \#)$$

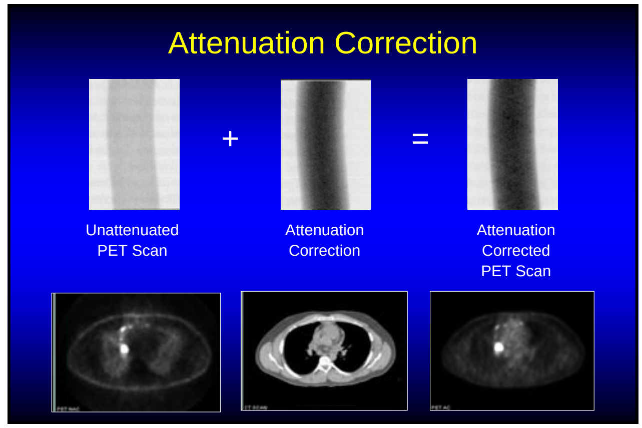
For CT# > 0

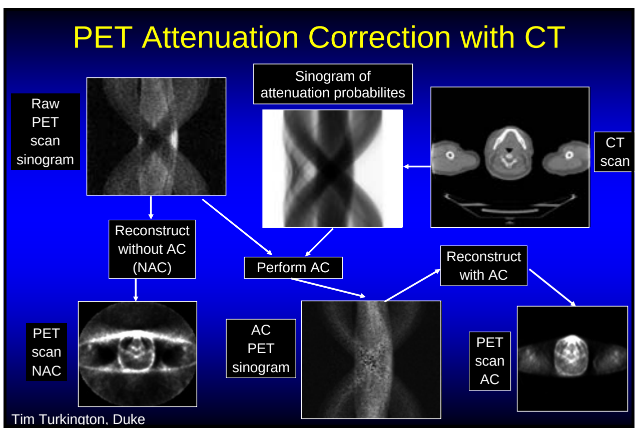
$$\mu_{511\ keV} = 9.61 \times 10^{-2} + 5.08 \times 10^{-5}\ (CT\ \#)$$

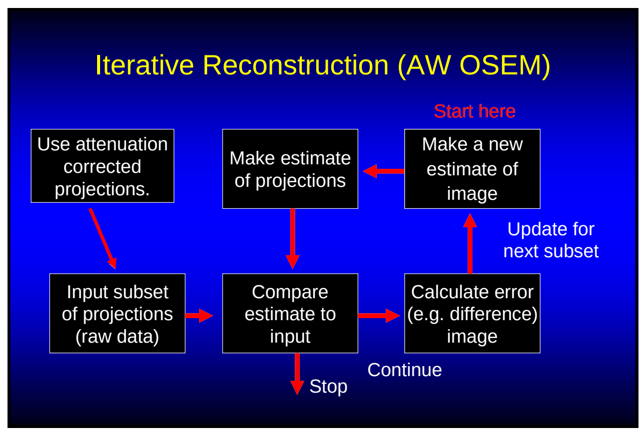
Attenuation Coefficients for 1 LOR

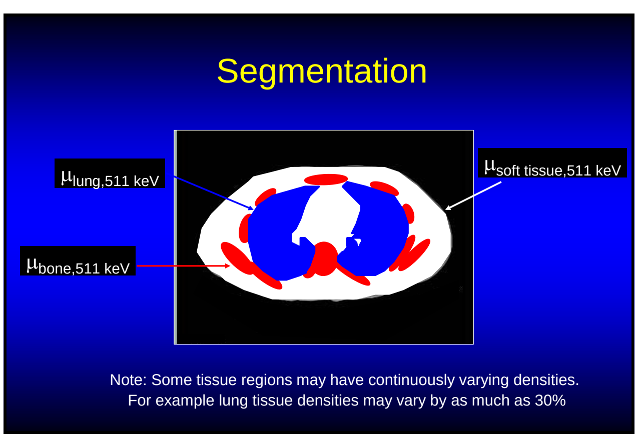


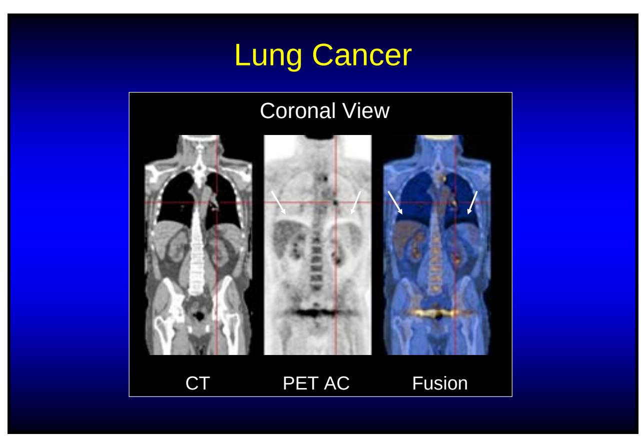

Y
X
θ
r
Sinograms
180º
θ
angle
0º
r
Position
A
B


Attenuation Correction
+
=
Unattenuated
PET Scan
Attenuation
Correction
Attenuation
Corrected
PET Scan


PET Attenuation Correction with CT
Raw
PET
scan
sinogram
Sinogram of
attenuation probabilites
CT
scan
Reconstruct
without AC
(NAC)
Perform AC
Reconstruct
with AC
PET
scan
NAC
AC
PET
sinogram
PET
scan
AC
Tim Turkington, Duke


Iterative Reconstruction (AW OSEM)
Start here
Use attenuation
corrected
projections.
Make estimate
of projections
Make a new
estimate of
image
Update for
next subset
Input subset
of projections
(raw data)
Compare
estimate to
input
Calculate error
(e.g. difference)
image
Continue
Stop


Segmentation
$\mu_{lung,511\ keV}$
$\mu_{soft\ tissue,511\ keV}$
$\mu_{bone,511\ keV}$
Note: Some tissue regions may have continuously varying densities.
For example lung tissue densities may vary by as much as 30%

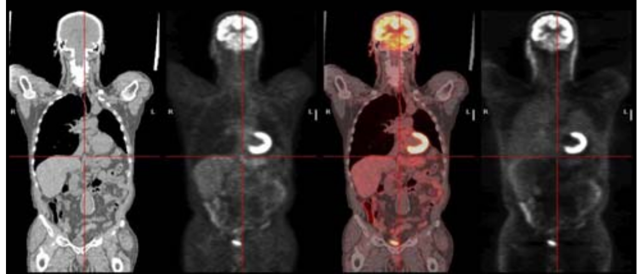

Lung Cancer
Coronal View
CT
PET AC
Fusion

CT Breathing Procotol for PET/CT

- Goal – Registration of PET and CT with:
  - Accurate attenuation correction
  - Accurate localization
- PET imaging is slow relative to breathing cycle
  - Could do respiratory gating to reduce motion
  - Without gating, image is an average of the breathing cycle
    - But, a weighted average, emphasizing end-expiration
- CT is fast relative to the breathing cycle
  - With <1 sec rotation times, each slice will represent a single respiratory phase
  - Could use respiratory gating to provide all phases for each slice.
  - Acquiring complete scan at end-expiration with breathhold gives reasonable match with PET.

Tim Turkington, Duke

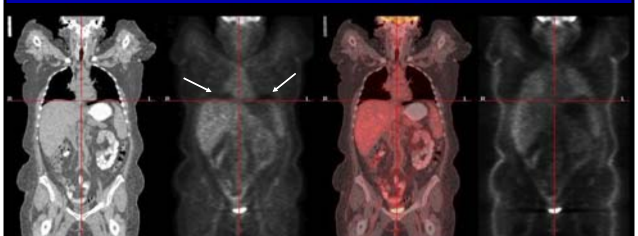
Good Match



CT | PET-AC | Fusion of CT + PET-AC | PET-NAC

Tim Turkington, Duke

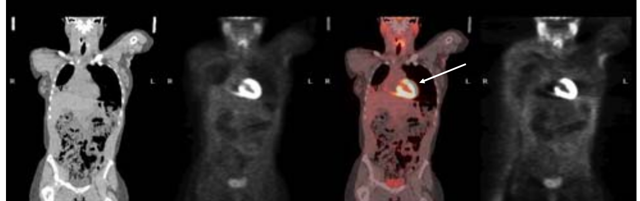
Diaphragm Mis-match



CT | PET-AC | Fusion of CT + PET-AC | PET-NAC

Tim Turkington, Duke

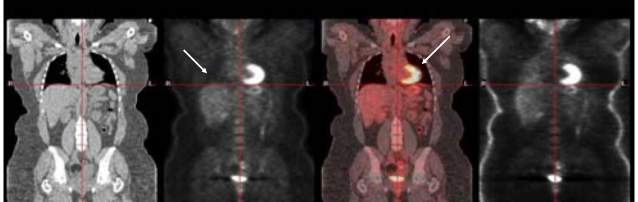
Heart Mis-match



CT | PET-AC | Fusion of CT + PET-AC | PET-NAC

Tim Turkington, Duke

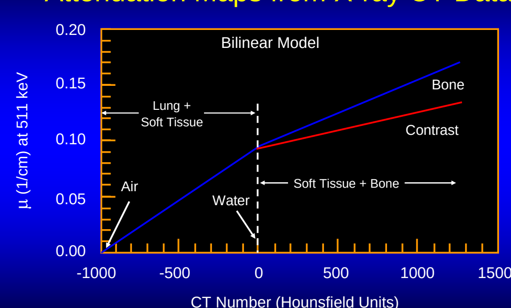
Okay?



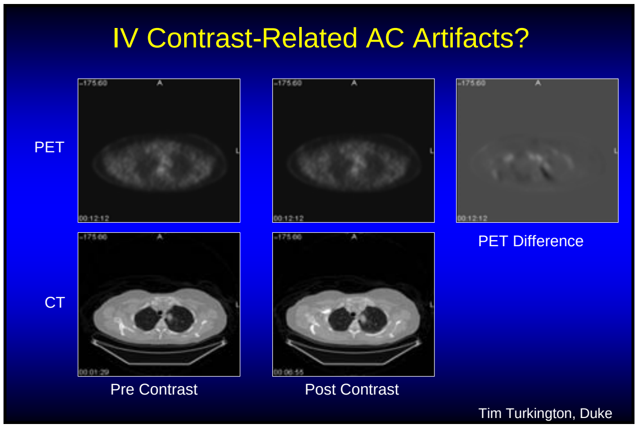
CT | PET-AC | Fusion of CT + PET-AC | PET-NAC

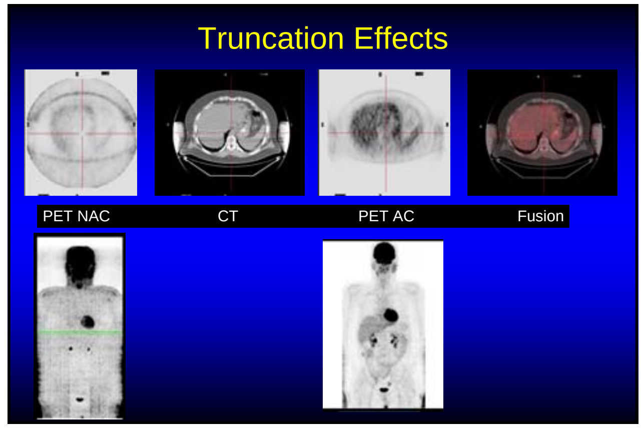
Tim Turkington, Duke

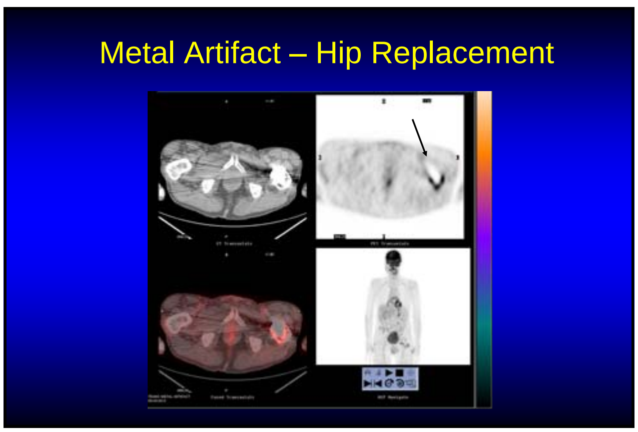
Calibration Curve for Scaling of Attenuation Maps from X-ray CT Data



Adapted from Blankespoor, et al, IEEE Trans. Nuc. Sci., Vol. 43 pp 2263-2274, 1996.


IV Contrast-Related AC Artifacts?
PET
CT
PET Difference
Pre Contrast
Post Contrast
Tim Turkington, Duke


Truncation Effects
PET NAC
CT
PET AC
Fusion


Metal Artifact – Hip Replacement

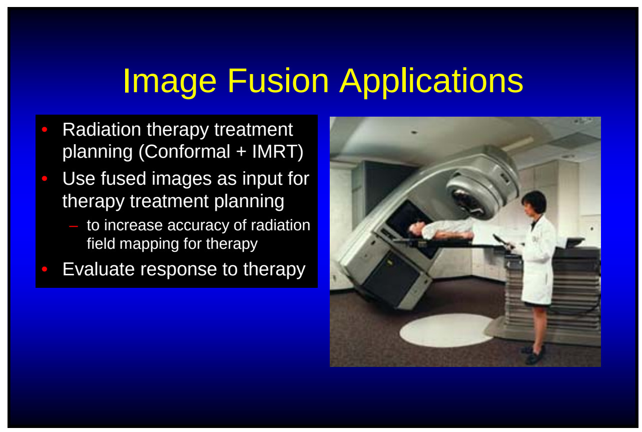
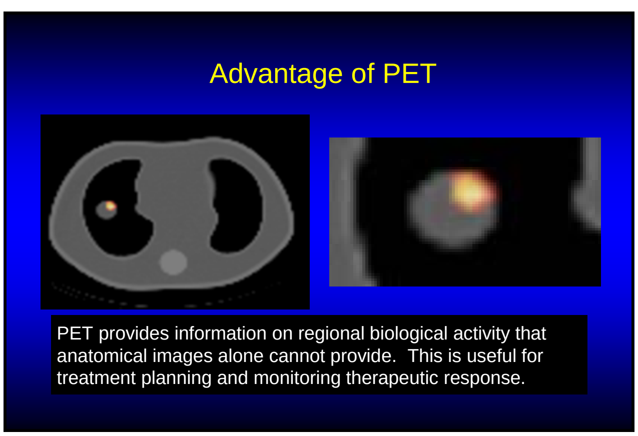
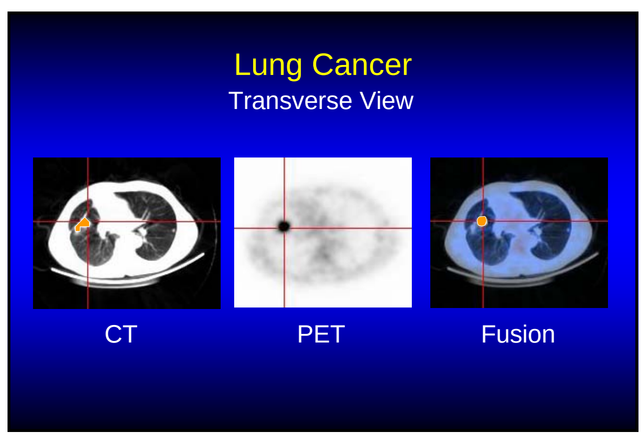


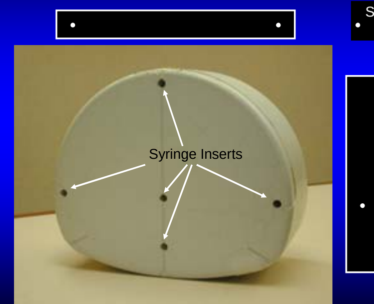
Image Fusion Applications
Radiation therapy treatment planning (Conformal + IMRT)
Use fused images as input for therapy treatment planning
– to increase accuracy of radiation field mapping for therapy
Evaluate response to therapy


Advantage of PET
PET provides information on regional biological activity that anatomical images alone cannot provide. This is useful for treatment planning and monitoring therapeutic response.

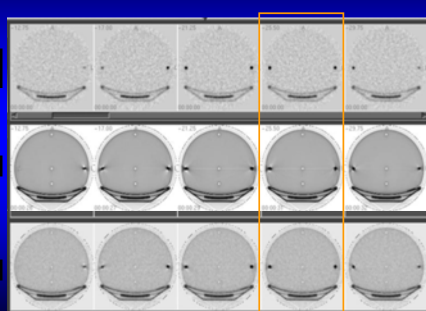

Lung Cancer
Transverse View
CT
PET
Fusion

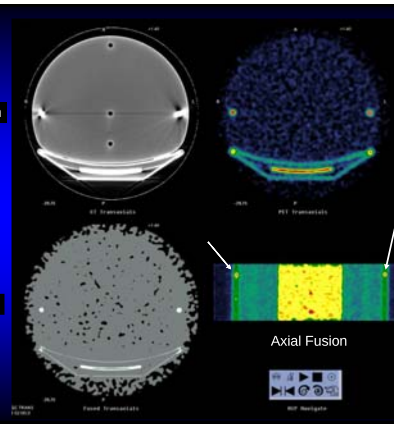
Quality Assurance

PET/CT Registration Phantom



PET/CT QC GE VQC





If not acceptable, reset gantry and repeat scans.
If still not acceptable, call service.

References

- Kinahan, PE, Hasagawa, BH, and Beyer, T, X-Ray-Based Attenuation Correction for Positron Emission Tomography/Computed Tomography Scanners, Seminars in Nuclear Medicine, Vol XXXII, No 3 (July), 2003: pp 166-179.
- Zaidi, H and Hasagawa, B, Determination of the Attenuation Map in Emission Tomography, J Nucl Med 2003; 44:291-315.
- PET Physics, Instrumentation, and Scanners, M.E. Phelps, Editor, Springer 2006

Acknowledgments

- Tim Turkington, Duke University