PET/CT Attenuation Correction and Image Fusion

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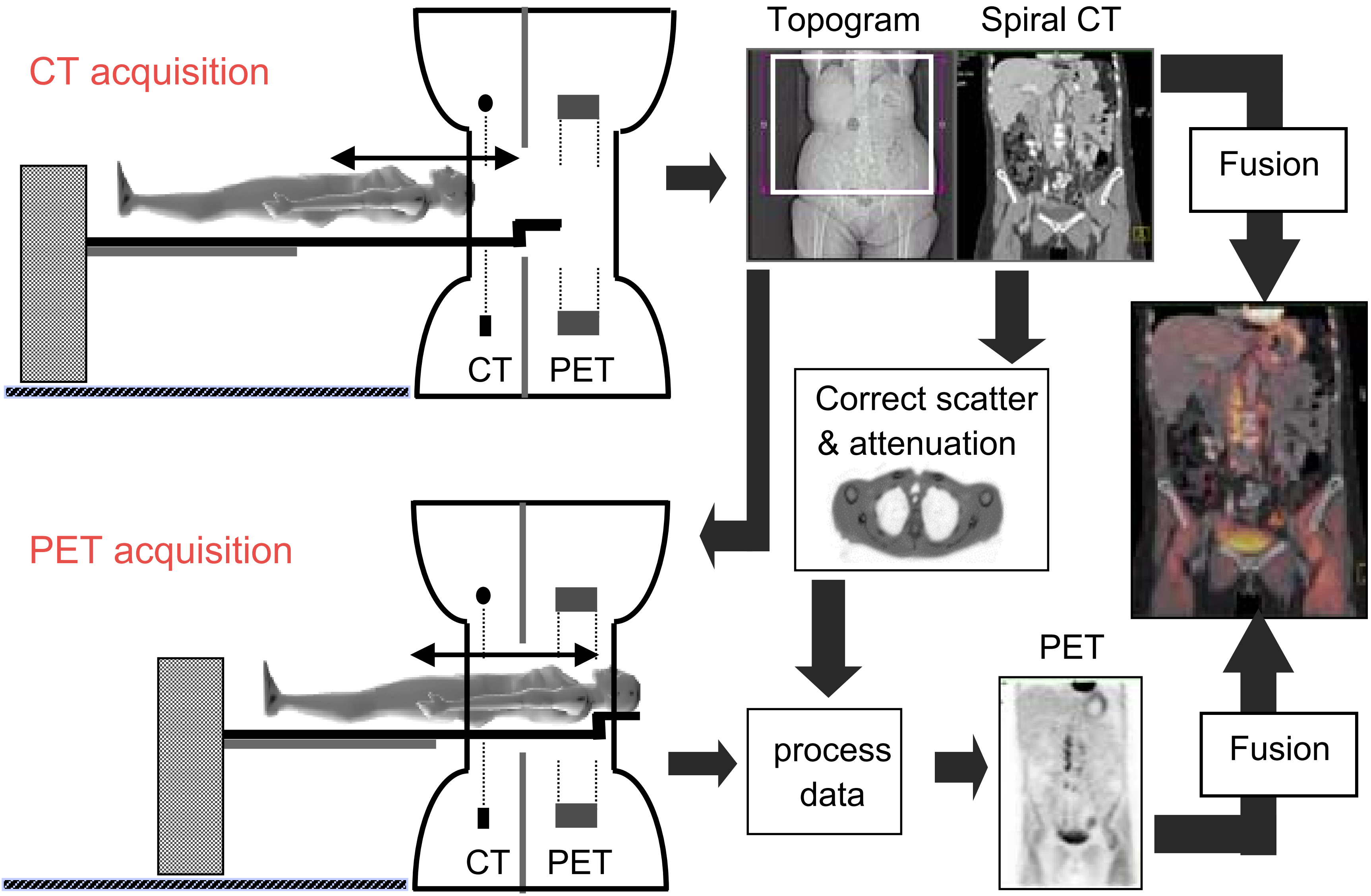
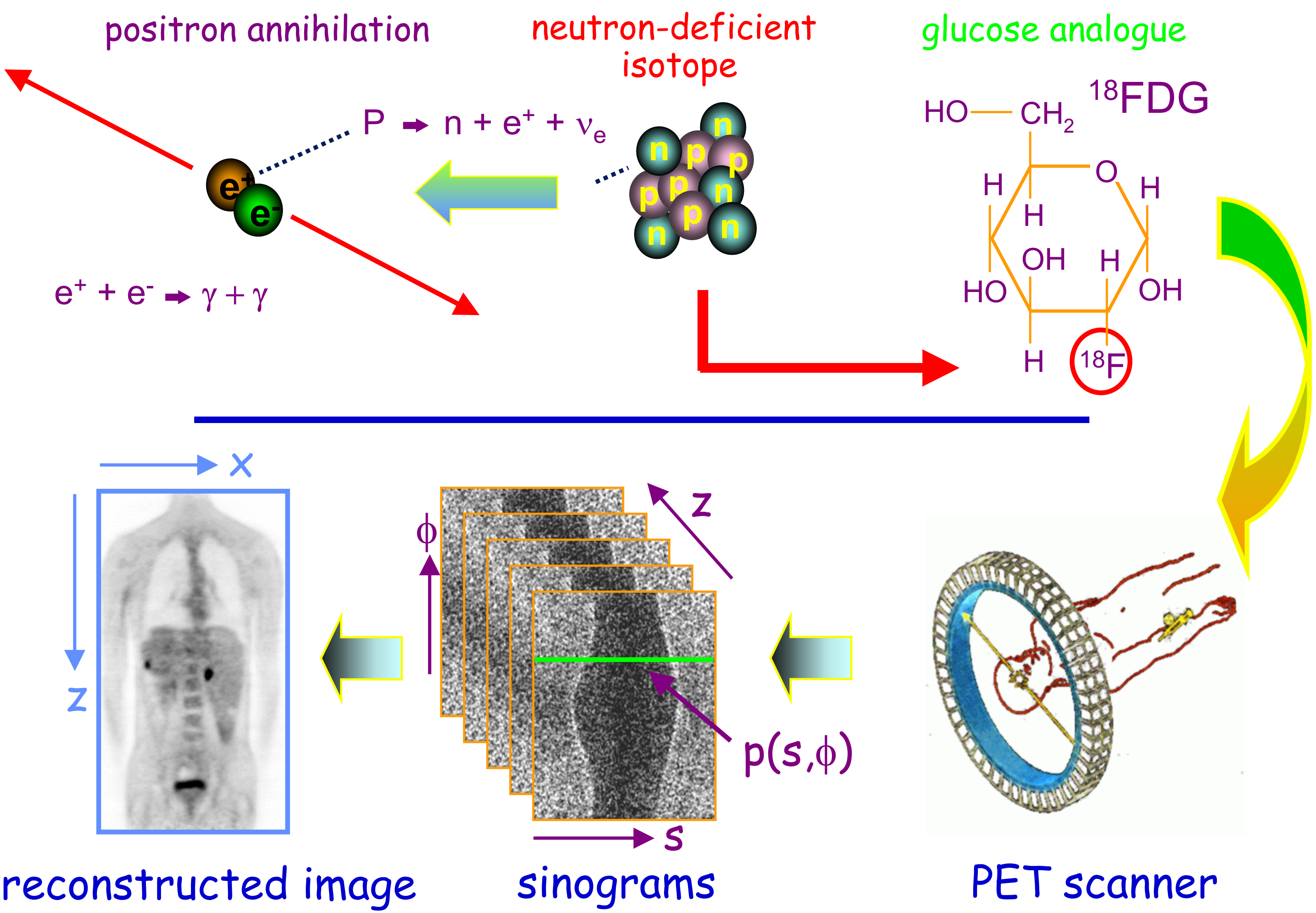
Overview of a PET/CT Scan



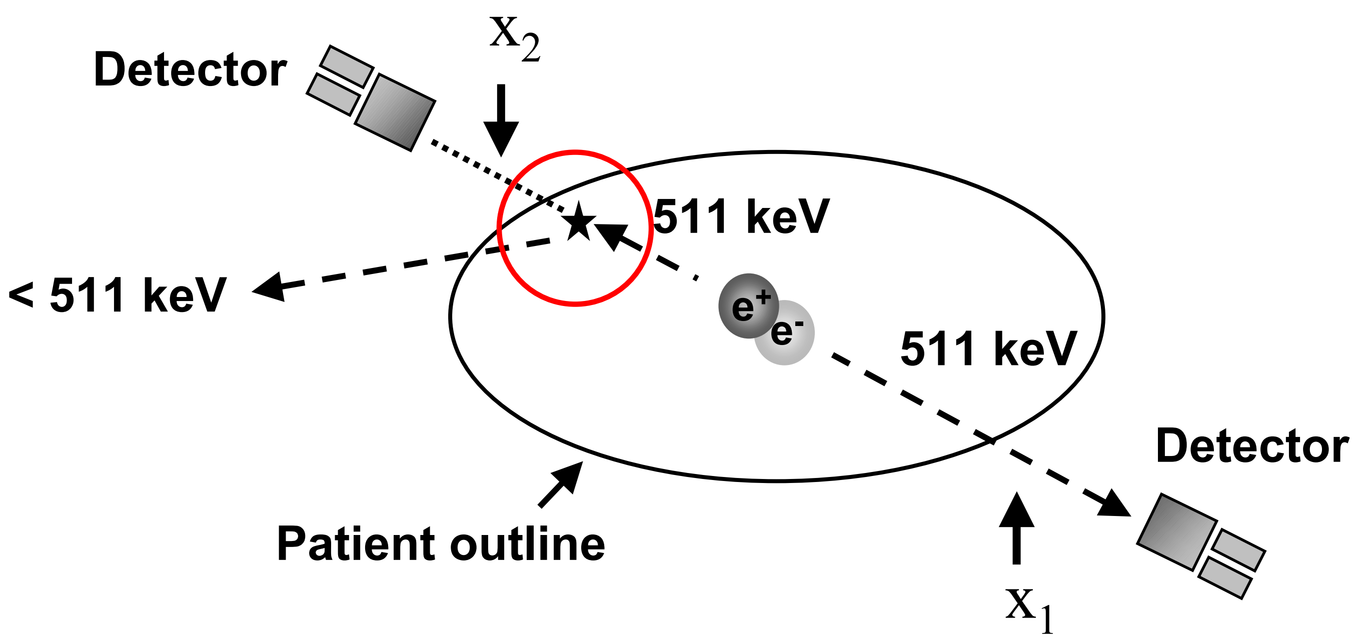
Part I – PET/CT Attenuation Correction

- Principles of attenuation correction (AC) in PET
- PET images with and without AC
- Principles of CT-based AC
- Energy scaling and tissue characteristics
- Optimized kVp dependent scaling
- Benefits of shorter acquisition times
- Respiration artifacts & protocols
- CT contrast agents.

Principles of PET imaging



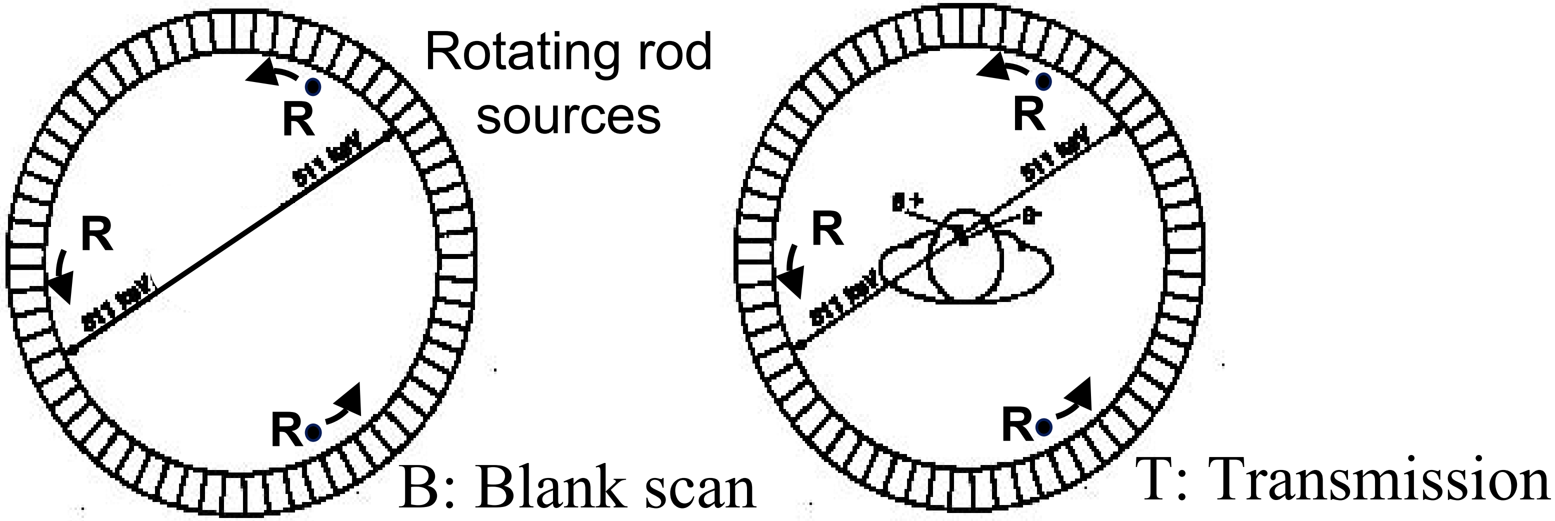
Emission signal attenuation



Scatter (and absorption) of the emitted photons by the body cause the true emission signal to be attenuated ➡ measure a lower signal.

Correct with attenuation correction factors ACF.

Principle of Attenuation correction



$$I(k) = I_0(k) \int_{x_1}^{x_2} \exp\{-\mu(x, E_{PET})dx\}$$

$$ACF = I_0(k) \,/\, I(k)$$
$$= B(k) \,/\, T(k)$$

PET scanners use sources to provide an essentially direct* measurement of the ACFs.

* May reconstruct transmission image and reproject to control noise.

Magnitude of the Attenuation correction factors

The ACFs are the factors by which the true source emission signal is suppressed by subsequent interaction with the body.

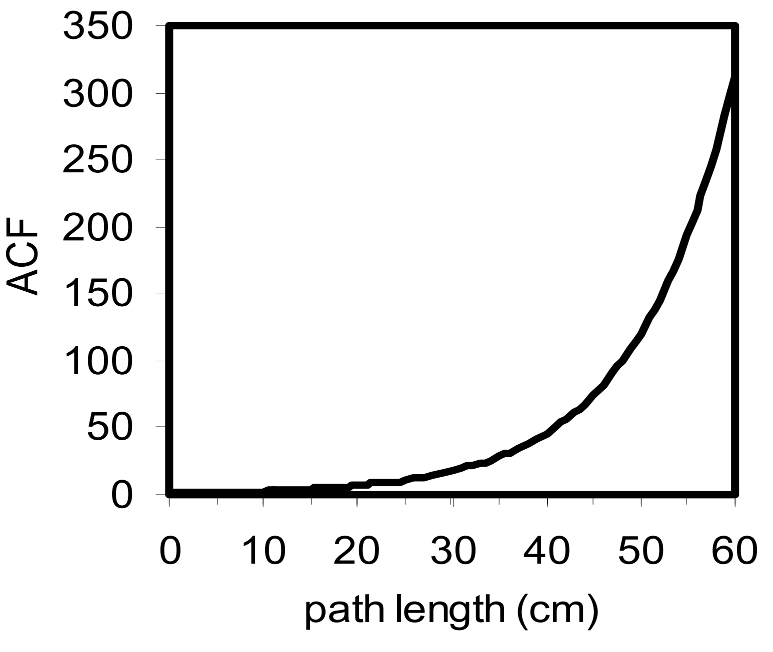
➡ multiply measured true event rate by ACF.

So how large are these factors?

Attenuation correction factors for pathlengths through water

Typical values for the ACFs through tissue:

20cm	~7
40cm	~50
60cm	~300



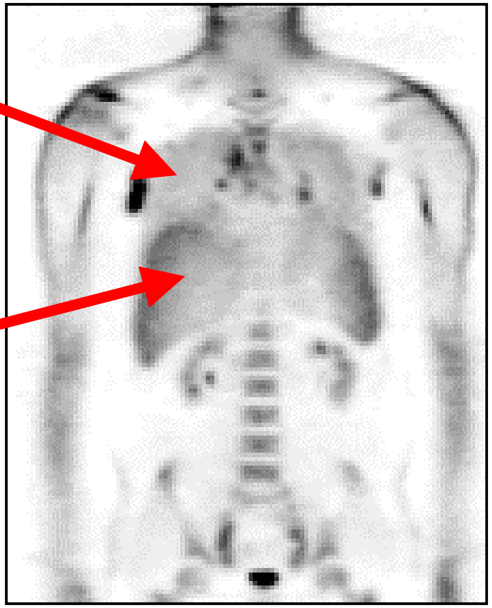
Attenuation correction - PET images

Can reconstruct PET images with or without attenuation correction applied:

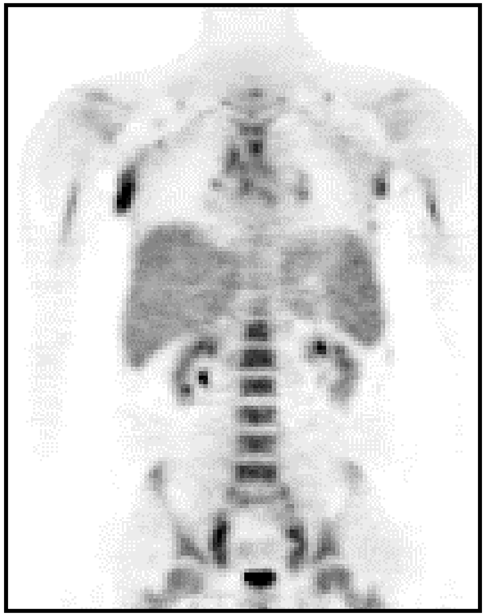
Features (non AC):

- not quantitative
- lungs appear "hot"
- suppression of inner activity relative to outer surface
  e.g. in the liver, also skin is relatively hot
- focal uptake still apparent

Without attenuation correction



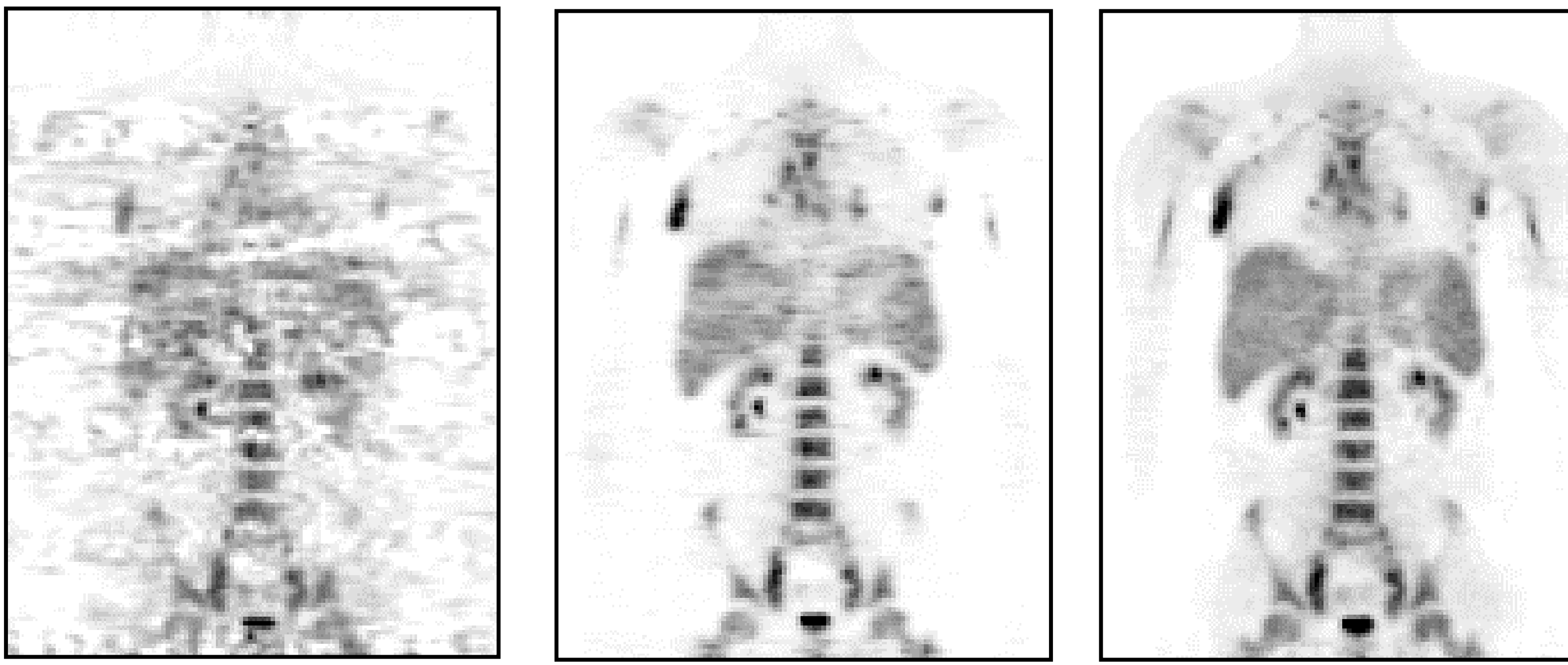
With attenuation correction



Attenuation-weighted iterative reconstruction

Can additionally use the attenuation correction factors for statistical weighting in iterative reconstruction:

<u>image reconstruction method</u>



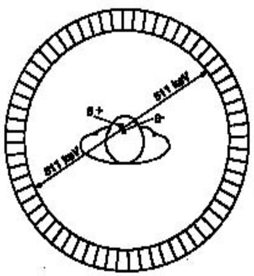
analytic inversion

iterative (statistical)

iterative (statistical) + attenuation weighting

Principles of CT-based attenuation correction

PET: Transmission-based AC:



measure line integrals
at (or near) 511 keV

reconstruct to
control noise

noisy 511 keV
attenuation map

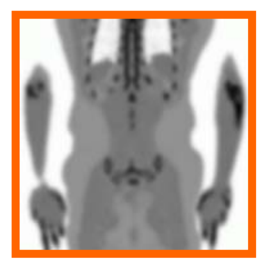
may segment
image and replace
with known values
to reduce noise

reproject ACFs

PET/CT: CT-based AC:

CT images correspond to
attenuation map at ~70keV

energy scaling
up to 511 keV



noiseless 511 keV
attenuation map

downsample and
smooth to PET
resolution

CT-based attenuation correction - some key points

- PET transmission (TX) scans are done at or near 511 keV.

  CT X-rays are much lower in energy <140keV.

  Need to energy scale CT images to 511 keV

- PET TX ACFs much noisier than CT-based ACFs

- CT-based AC eliminates the need for a transmission scan.

  Therefore no need for sources and blank scan.

  Still need to calibrate the PET detectors, of course:
  (normalization, 20cm Germanium phantom acquisition)

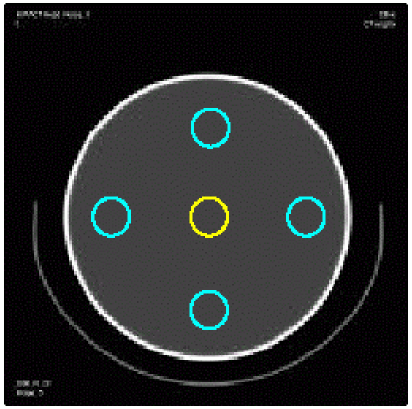
CT images - what are they?

CT scannners "measure" local photon linear attenuation μ

(at ~70 kev, the effective energy of the x-ray beam)

Hounsfield unit: $\mu \rightarrow HU = 1000 \times \dfrac{\mu - \mu_{water}}{\mu_{air} - \mu_{water}}$

-> air = -1000 HU, water = 0 HU



Calibrate using 20cm water phantom

CT number uniformity:

0 HU ± 4 HU (< 0.5 %)

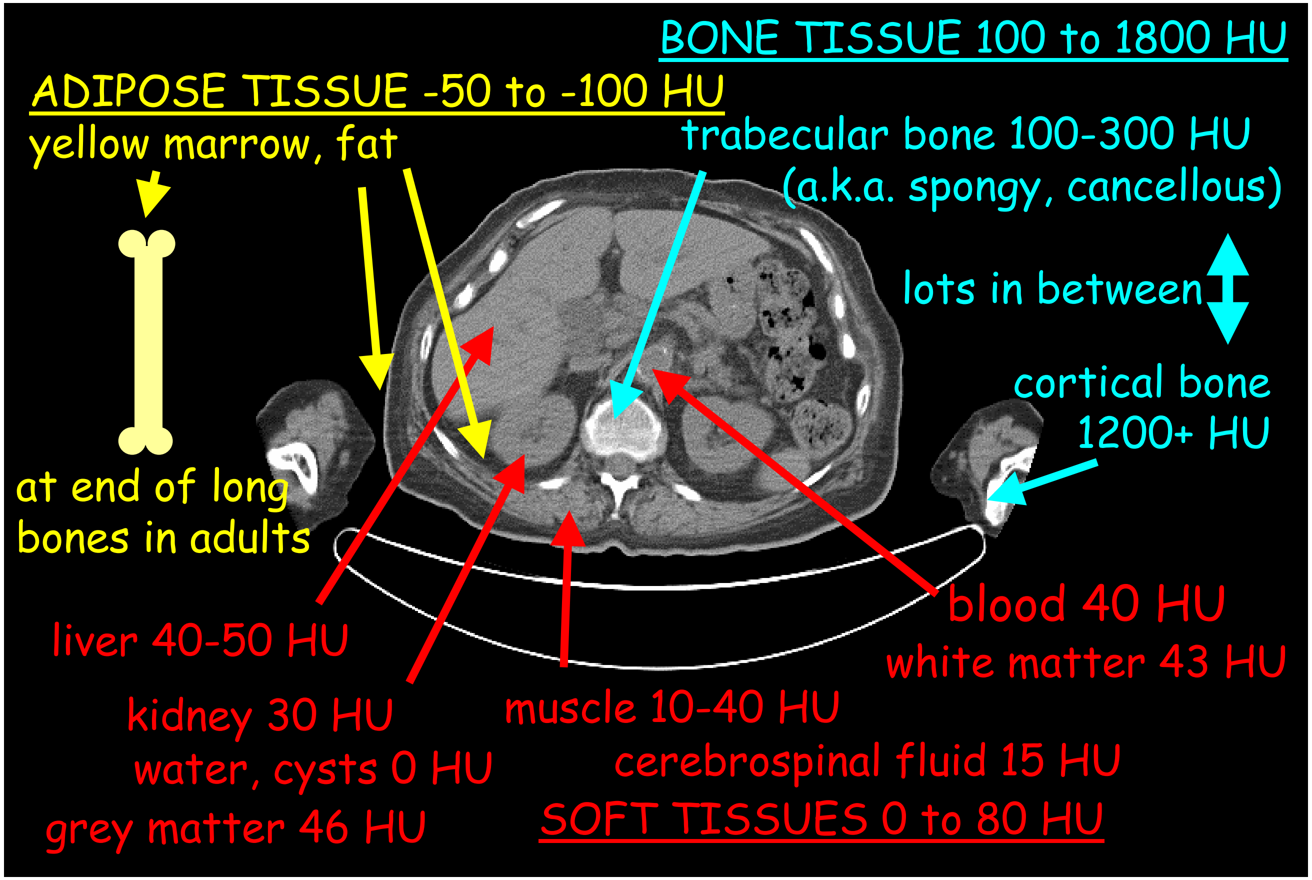
~10 HU difference

-> 10/1000 *100%

= ~1% difference in linear attenuation

X-rays used in CT have lower energy that PET 511 keV photons - will need to scale up in energy to perform AC.

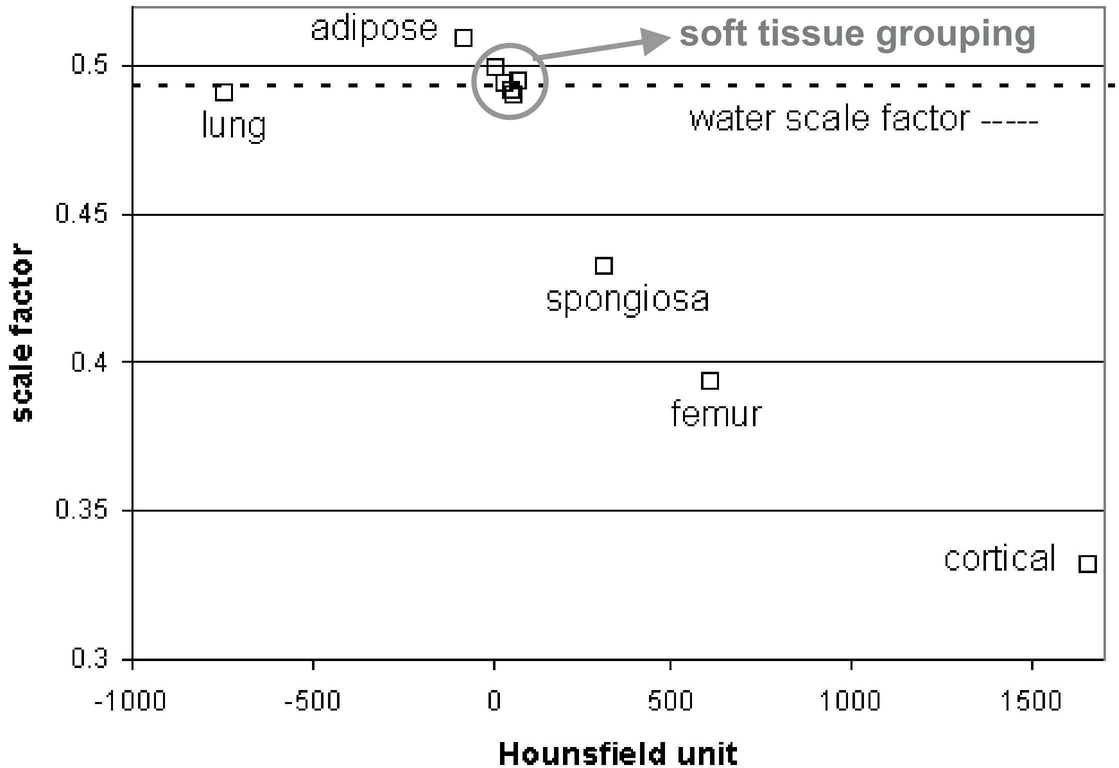
Hounsfield units of human tissues



Need to relate HU for these tissues to attenuation values at the PET energy of 511 keV

Tissue characteristics: energy scaling CT ➡ PET

$$\mu\ (511\ \text{keV}) = \mu\ (\text{CT}) \times \text{scale\_factor}$$

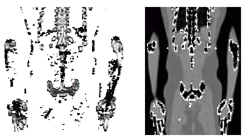


soft tissues all similar, bone scale factors lower

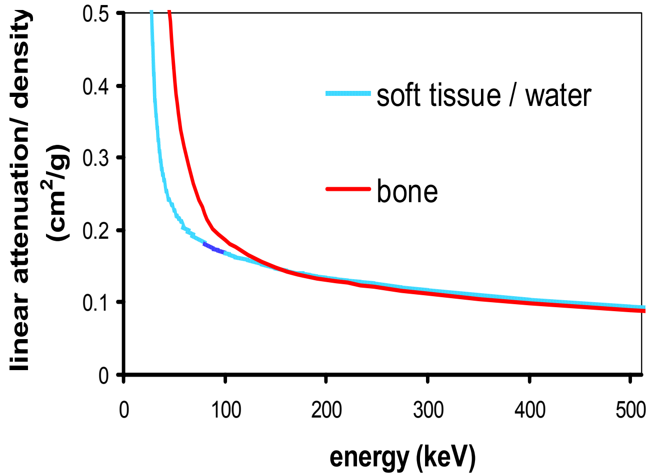
data based on ICRP 1975 tissue chemical compositions

Scaling algorithms

Threshold model:

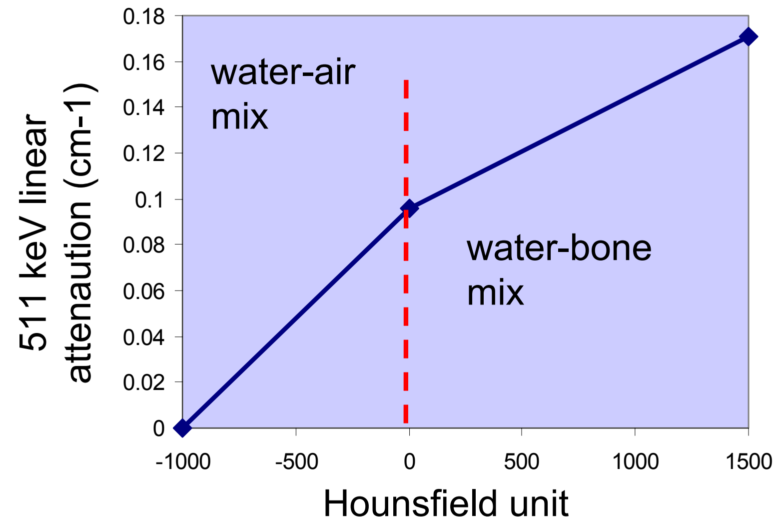


Threshold to separate bone and soft tissue in CT images (~300HU).



Scale each separately to 511 keV, combine to form 511 keV image

Mixing model:



Assume Hounsfield unit is determined by a mixture of two components with known densities & scale factors.

Breaking point H.U. < 0 water-air mixture

Breaking point H.U. > 0 water-dense bone mixture

These methods as described not account for different kVp & make assumptions about the locations of thresholds and breaking points.

kVp dependent energy scaling

CT scans at different kVp settings correspond to different effective energies ➡ generalize to kVp dependent scaling.

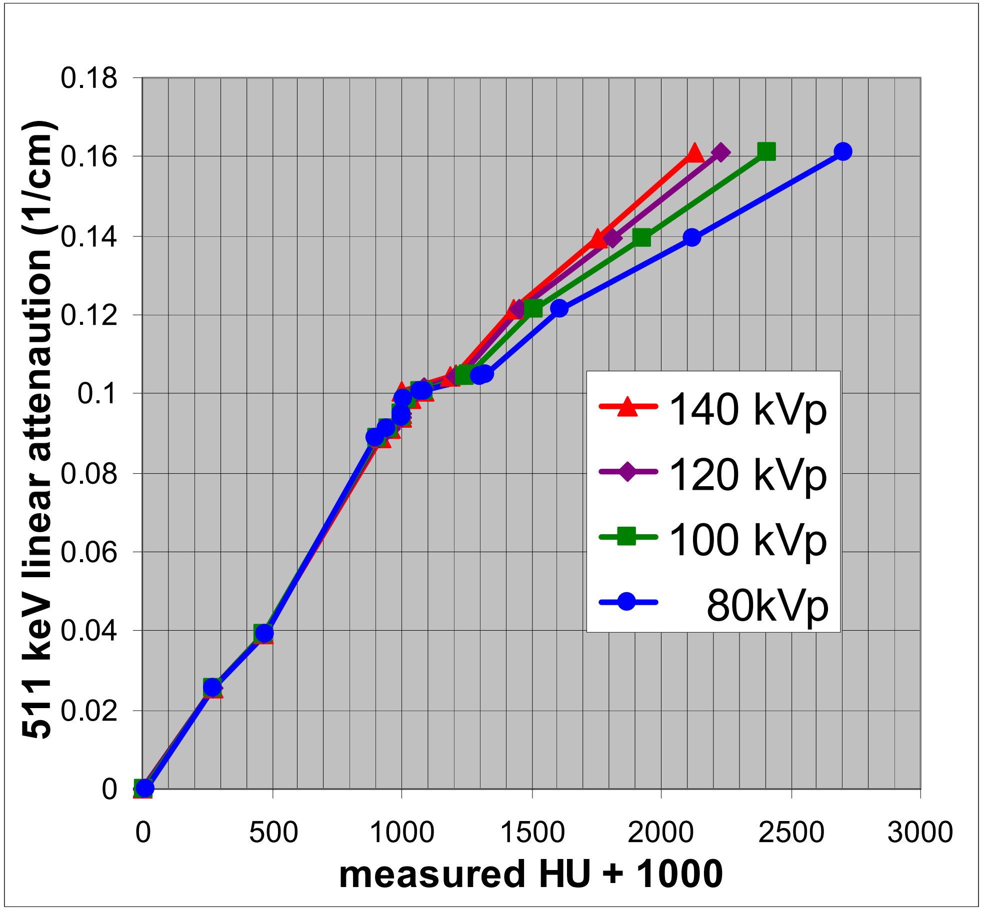
possible values:

80,100,110,120, 130,140 kVp

Reference tissues in a Gammex 467 electron density phantom are measured at all kVp.

Scaling function is a bilinear fit to measured data at each kVp.

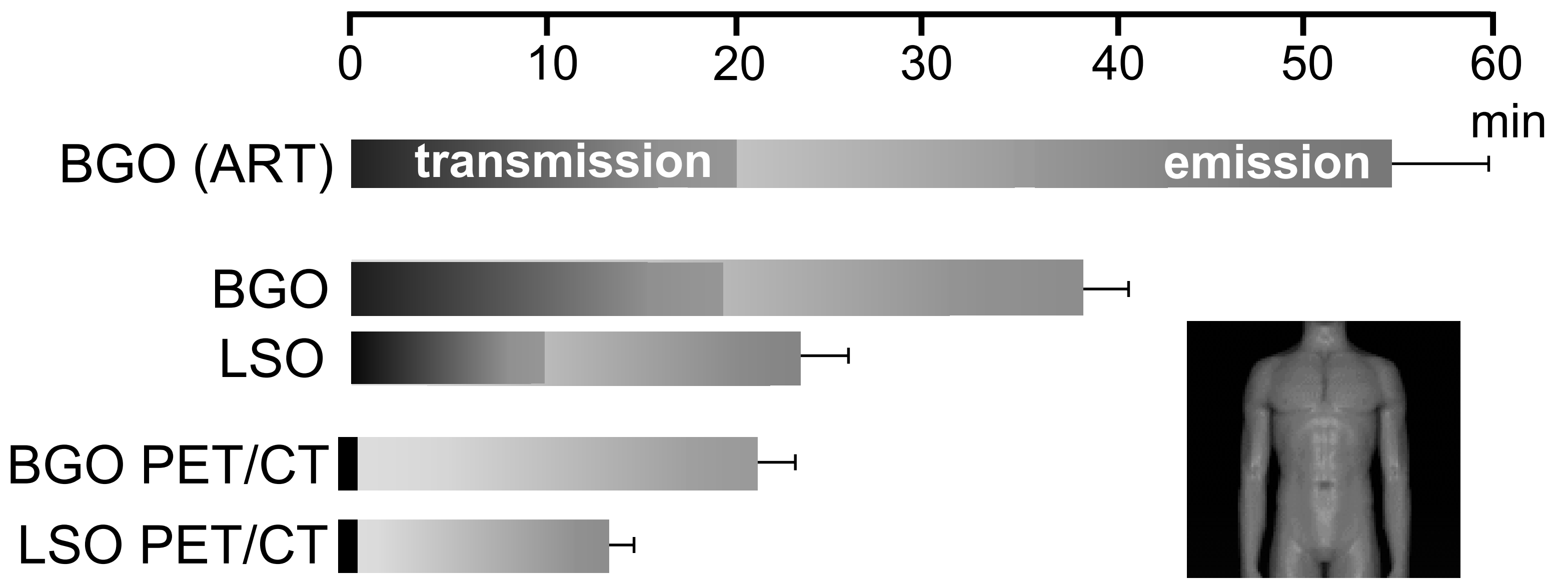
Breaking point found to be at ~60 H.U.



Progression of clinical whole-body scan times

CT-based AC obviates the need for a transmission scan

⇨ faster total scan times



CT respiration protocols in PET/CT

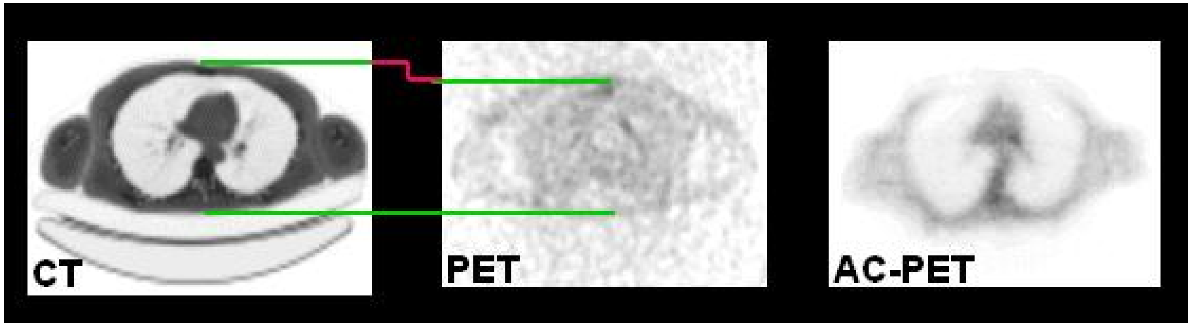
During the PET acquisition the patient is breathing shallowly - averaged over many cycles.

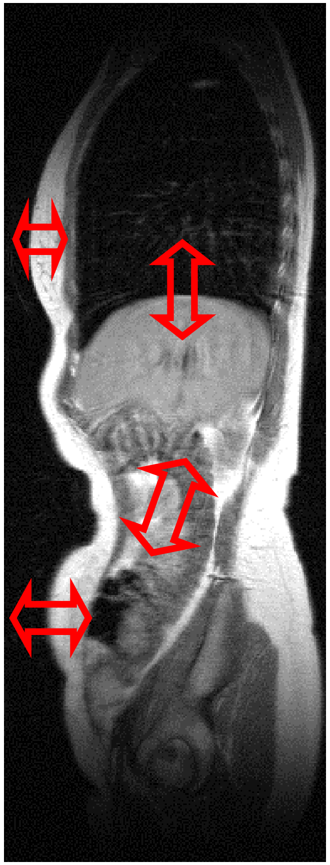
Usual CT protocol is full (deep) inspiration breathold:

eliminates motion, but leads to maximum mismatch with PET.

Other possibilities are CT with shallow breathing (a.k.a. tidal, quiet) or partial inspiration breathold.

Mismatch between full inspiration CT and PET can lead to the "vanishing chest wall" artifact.



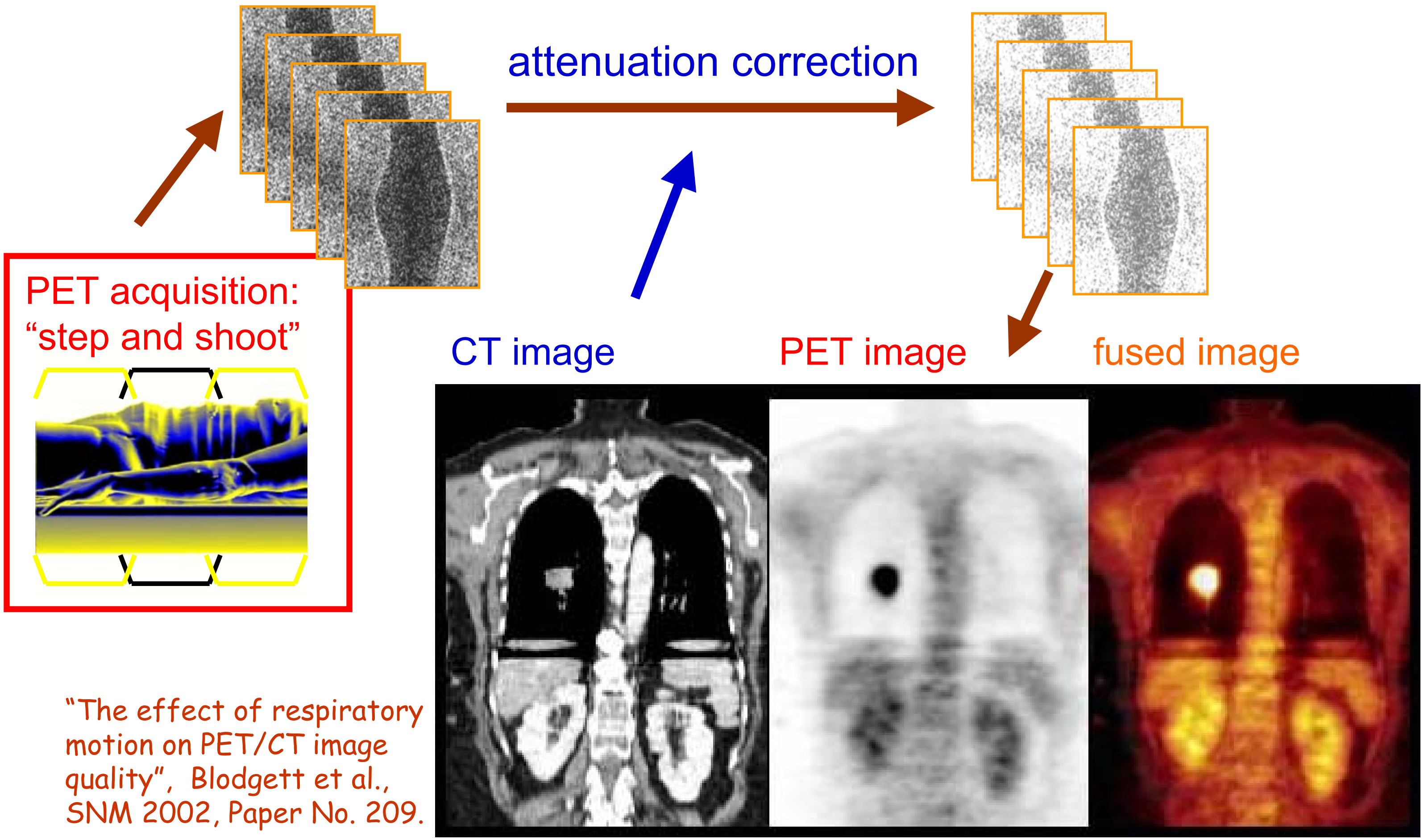


typical max. excursion:

deep ~10cm
shallow ~2cm

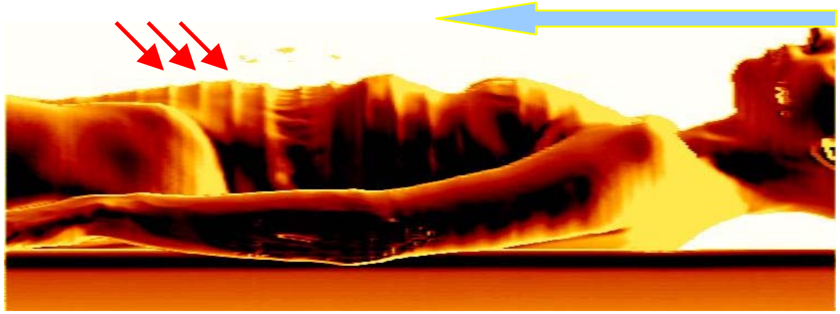
Respiration artifacts: propagation into PET

Single slice CT with tidal breathing can lead to geometric distortions:



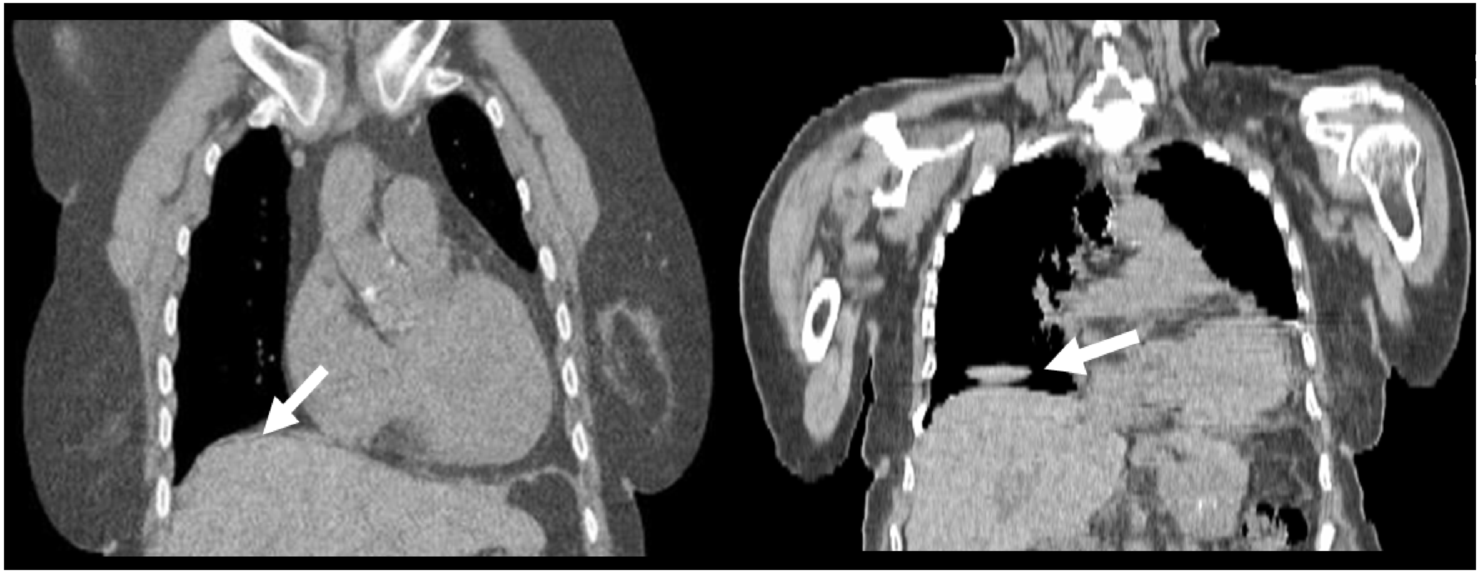
"The effect of respiratory motion on PET/CT image quality", Blodgett et al., SNM 2002, Paper No. 209.

Respiration artifacts: multislice CT



single slice CT

tidal breathing throughout spiral acquisition



16 slice CT, tidal breathing

single slice CT, tidal breathing

Whole-body (neck through pelvis) CT study ~16 sec (16 slice), 90sec (single slice).

Geometric distortions in CT images less severe with 16 slice compared to single slice.

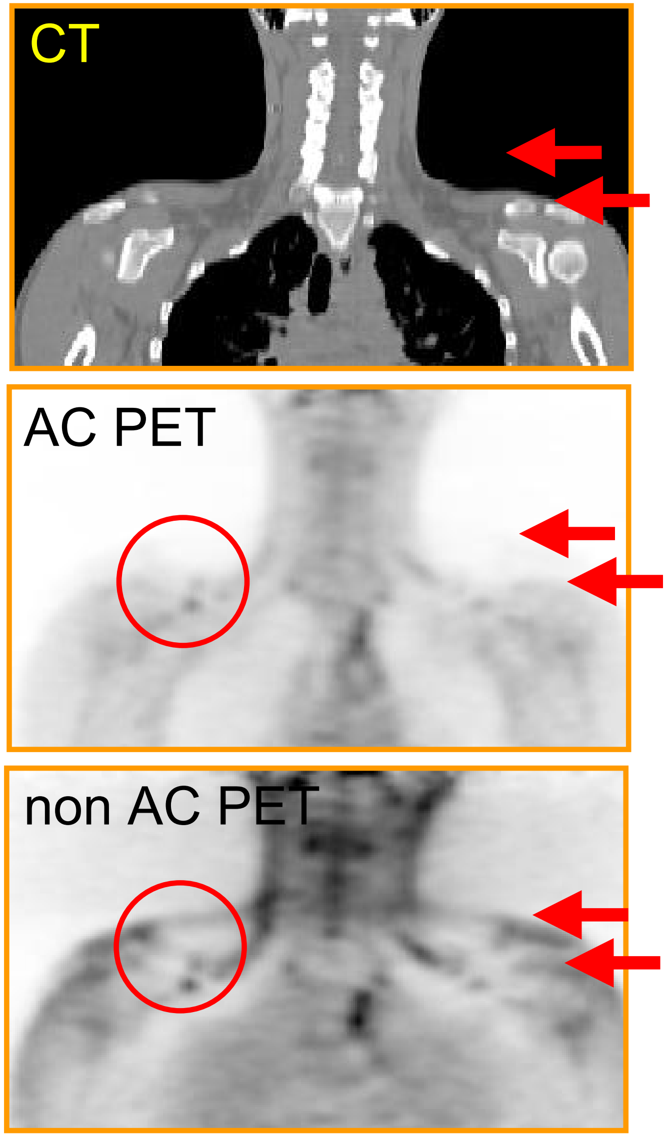
Other types of patient motion

Type of motion & typical timescale	
cardiac	~ 1s
respiration	~ 4s
peristalsis	minutes
muscular spasms	unpredictable
patient motions	unpredictable

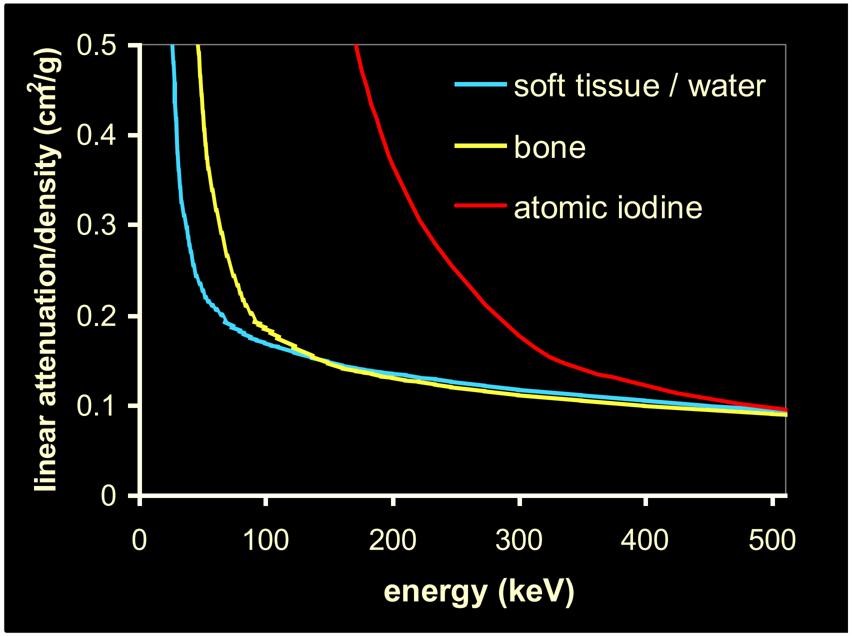
Example:

AC PET shows "shadowing" of focal uptake?

NON AC PET shows patient moved shoulders ~midway through PET acquisition.



Properties of CT contrast agents



<u>Contrast agent:</u>

is a solution of a highly attenuating high atomic number (Z) element

tolerable agents: iodine (Z=53) , barium (Z=56)

locally raises HU

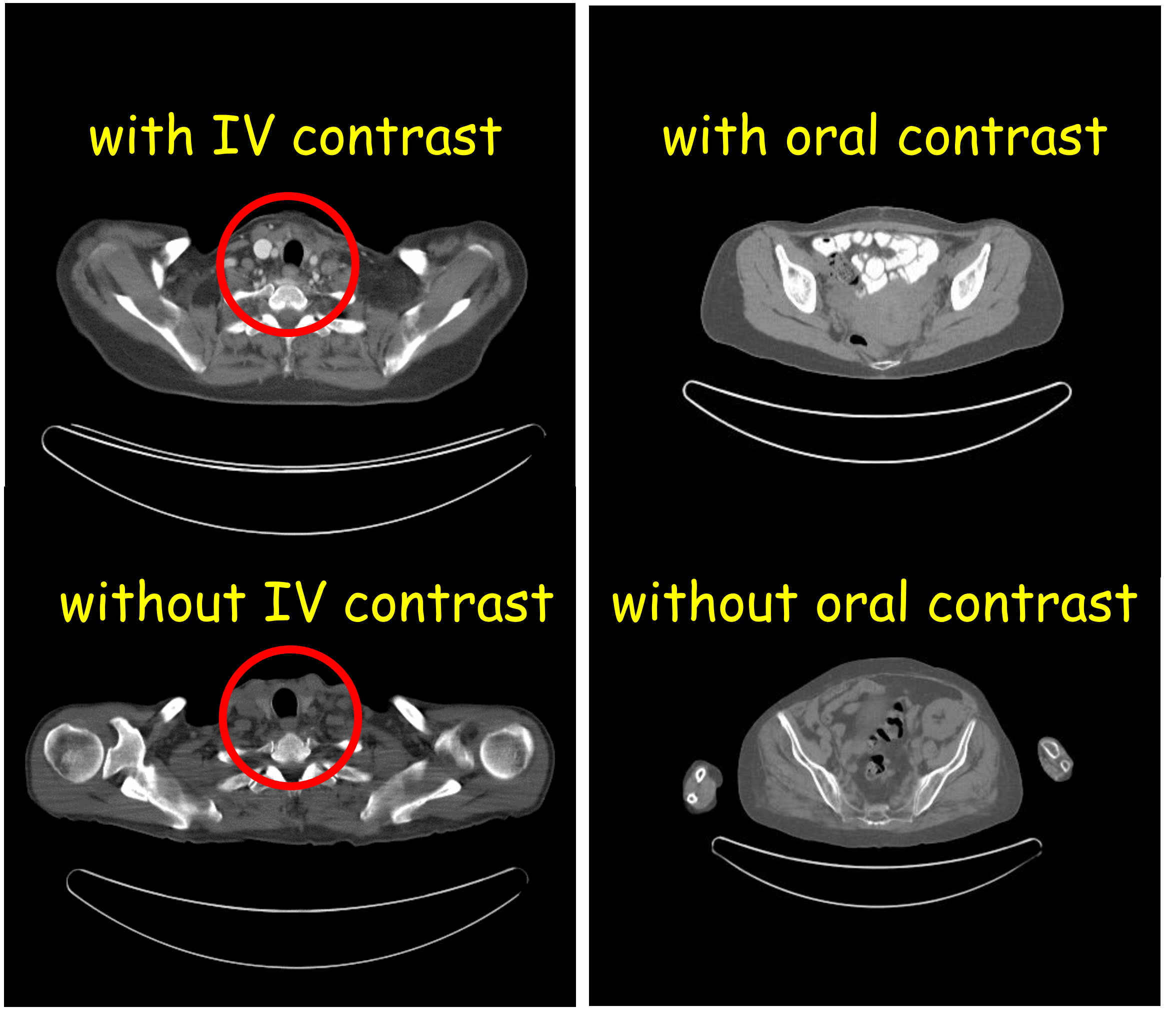
<u>Oral contrast agent</u>: dilute solution of barium sulphate or organically bound iodine is swallowed, generally well tolerated

<u>IV contrast agent</u>: automated intravenous injection of an iodinated contrast bolus, small risk of an adverse reaction

Use of CT contrast agents

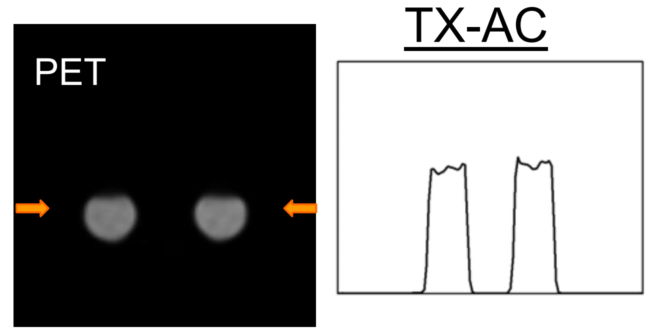
CT contrast agents can improve the diagnostic utility of the CT images.

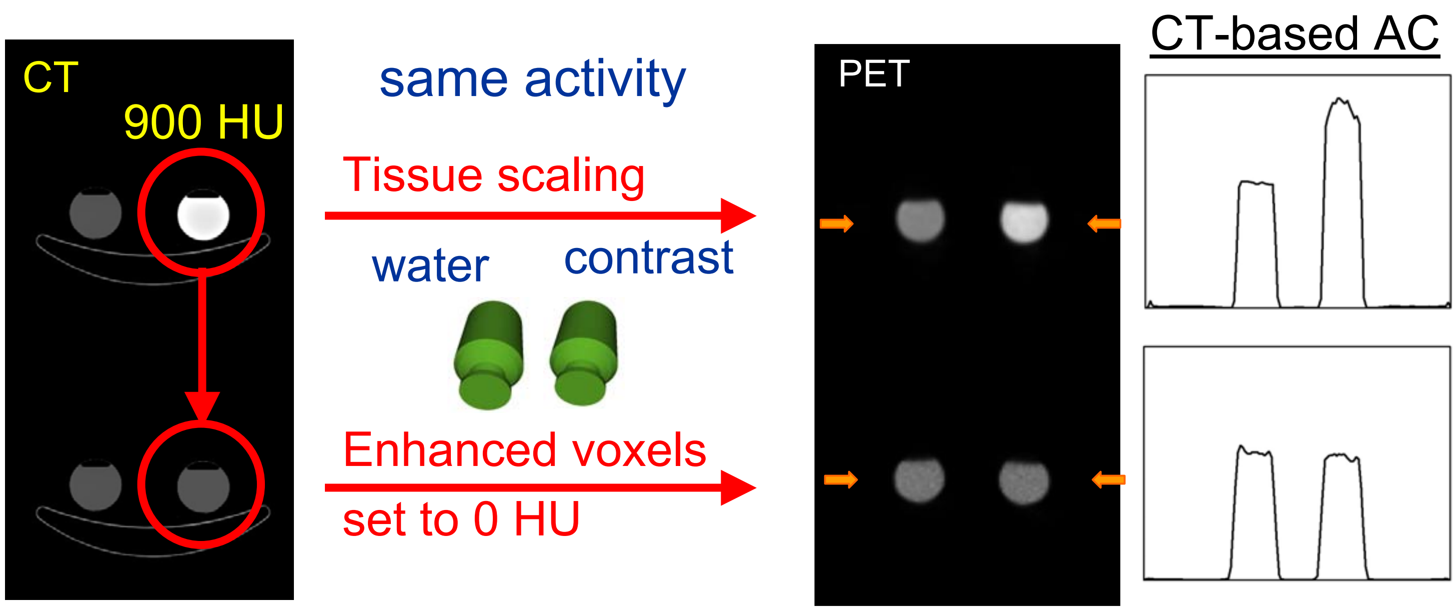
Do not affect PET except may introduce generally small biases through attenuation correction.



Oral contrast agent bias in PET images

The correct attenuation at 511 keV can be approximated by replacing the enhanced CT values by the value for water, which will scale to the correct attenuation value for water at 511 keV.





For typical values in patients (<900 HU) bias is generally modest.
Will be larger in cases of contrast precipitation and IV bolus.

Part II - PET/CT Image Fusion

- Review of fused image display
- Software versus hardware fusion
- Localization utility of CT in PET/CT
- Interpretation of fused images:
    - Understanding artifacts
- Use of software fusion in PET/CT.

Review of fused image display

- Typically have CT, PET, fused images
- transverse, sagittal, coronal sections
- linked cursors, pixel and ROI values

<u>Alpha Blending</u>: method for fused display of two (color) images

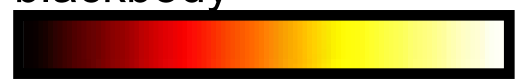
α (0⇔1) gives opacity of overlayed image [α=1 fully opaque, α=0 fully transparent]

<u>COLOR TABLES</u>

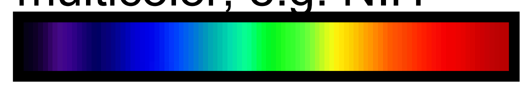
inverse greyscale

greyscale

blackbody



multicolor, e.g. NIH



CT image:

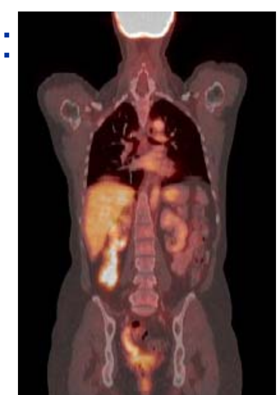
greyscale

report Hounsfield units

PET image:

inverse greyscale

report SUV or bq/ml



Fused image:

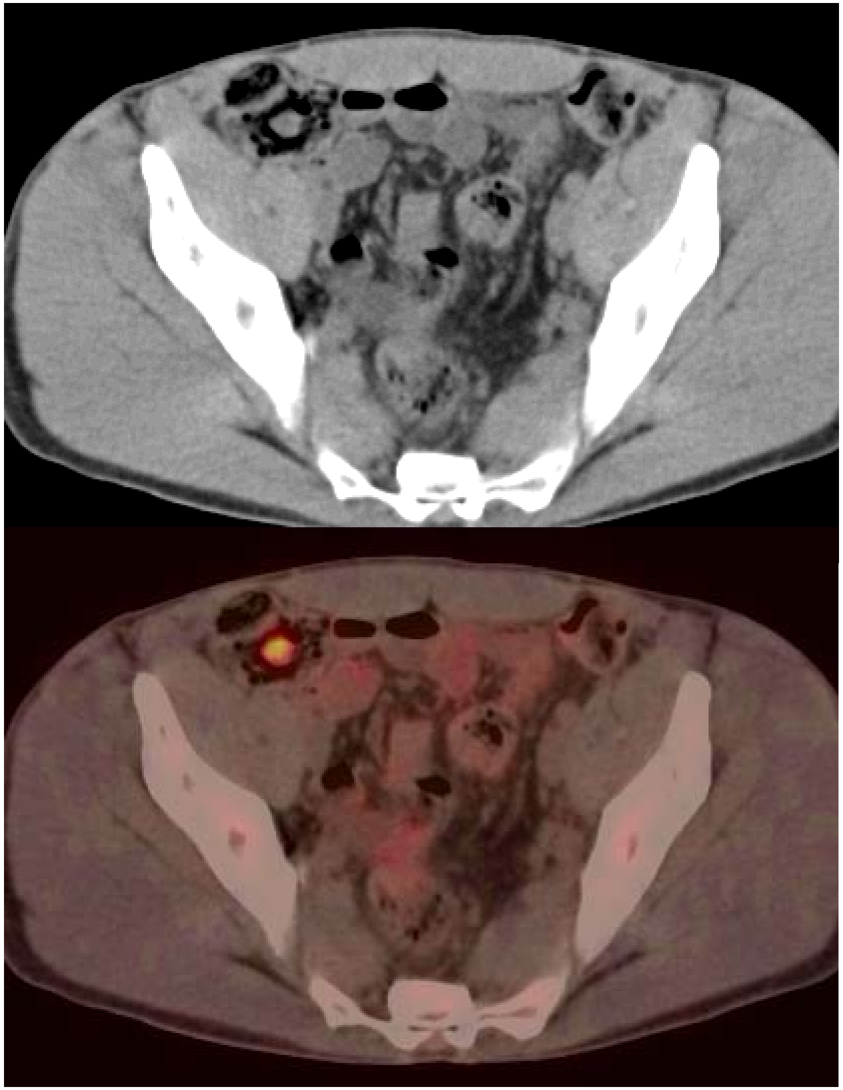
alpha-blended

greyscale(CT) & blackbody(PET)

PET images +CT images versus PET/CT scan images

Software fusion	Hardware fusion
Access to image archives required	Images immediately available
Carefully-controlled patient positioning	Single-patient positioning
Different scanner bed profiles	Same bed for both scans
Internal organ movement	Little internal organ movement
Disease progression in time	Scans acquired close in time
Limited registration accuracy	Improved registration accuracy
Inconvenience for patient (2 scans)	Single, integrated scan
Labour intensive registration algorithms	No further alignment required

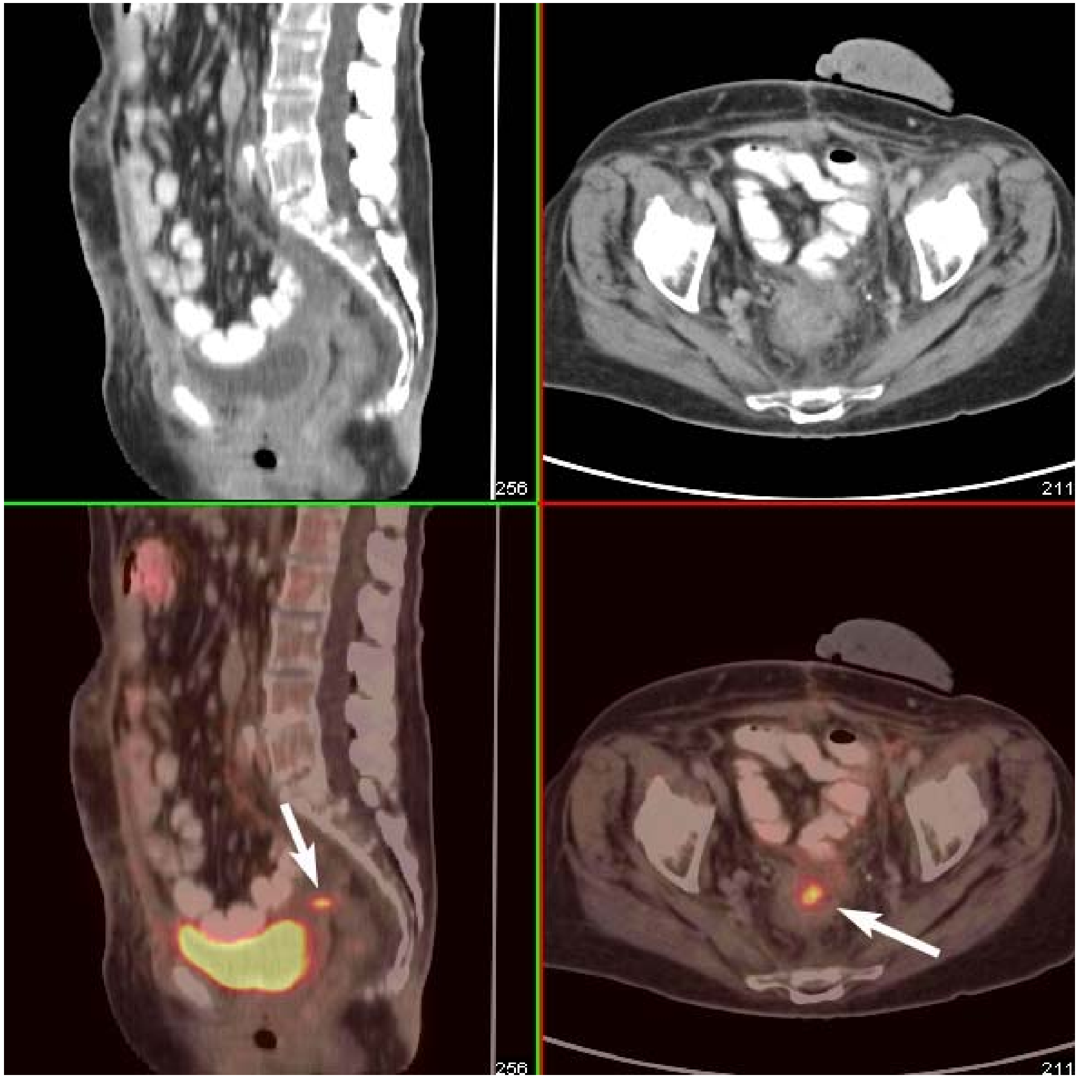
Localization advantages of PET/CT - example 1



incidental finding in right pelvis on PET

correlation with CT shows focus within right colon

Localization advantages of PET/CT - example 2



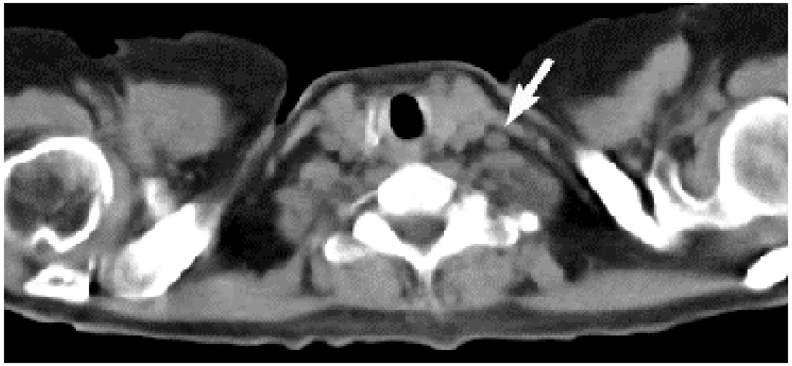
Ovarian cancer:

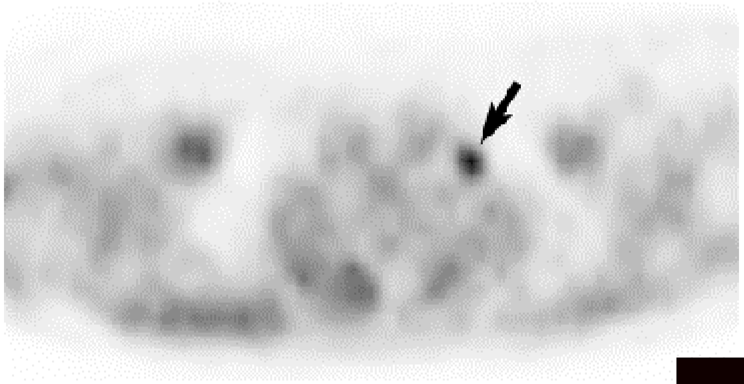
CT shows post surgical changes in the pelvis

PET reveals focal uptake at surgical site - suspicious for tumor

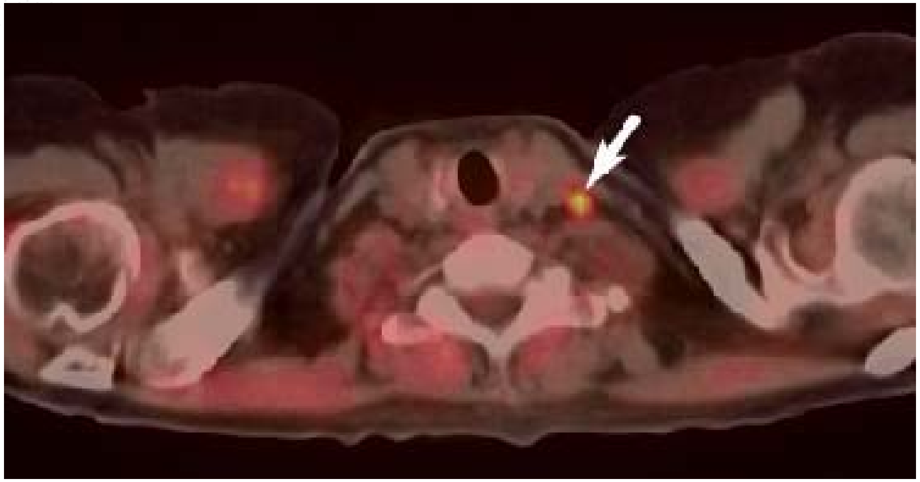
Localization advantages of PET/CT - example 3

Ovarian: CT shows small lymph node at the left neck base, within normal limits:





PET scan shows corresponding focal increase uptake specific to same node

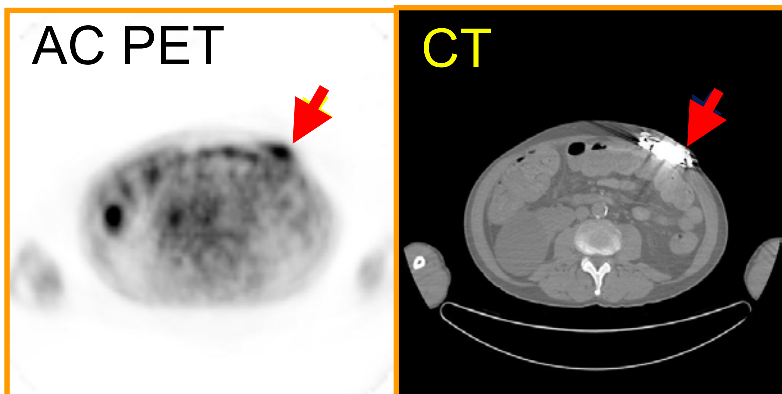


Interpretation of artifacts in fused images

Tissue scaling of <u>non-tissue high H.U. features</u> in the CT images can lead to artifactual increased focal uptake.

prosthetics, metal, bolus IV contrast, contrast precipitate

Can be interpreted through review of the CT images and, for further confidence, the non-AC PET images.



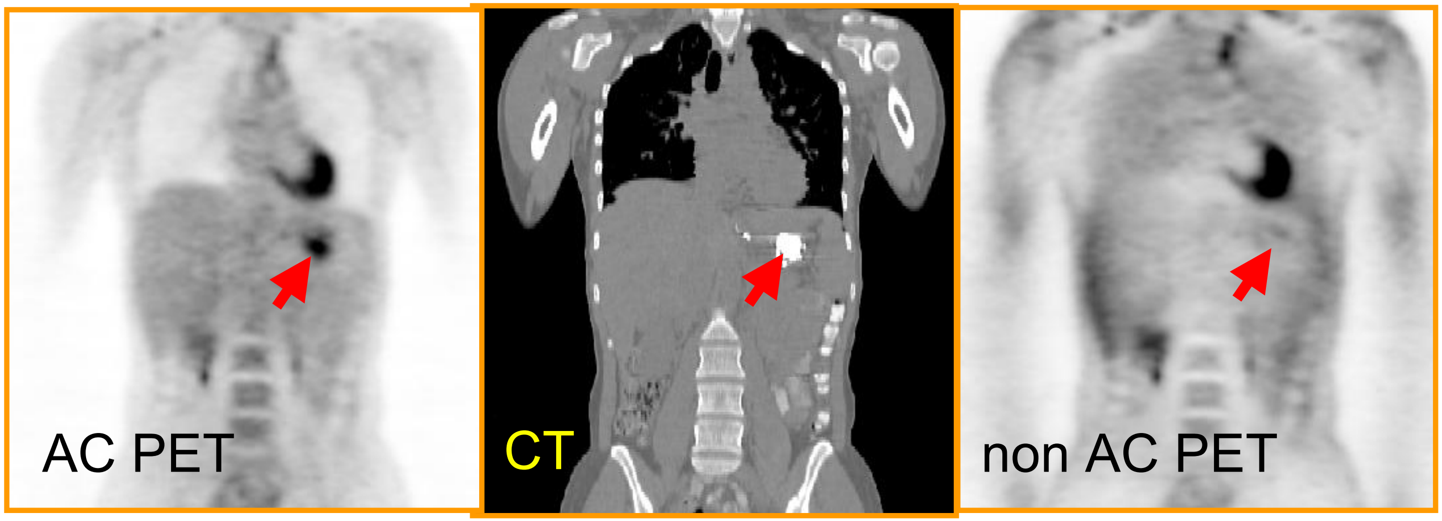
Subcutaneous titanium-lined chemotherapy port artifact

IV contrast bolus artifact

Interpretation of artifacts in fused images contd.

Suspected artifactual uptake in the stomach is seen to correlate with very high H.U. on CT (due oral contrast precipitation in the stomach).

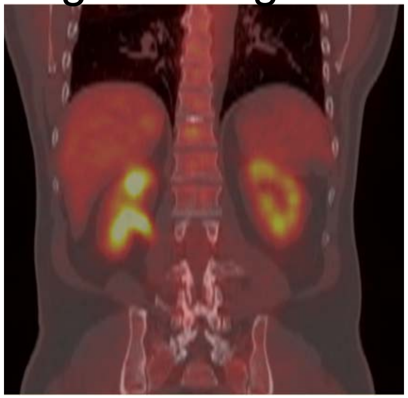
The non-AC image shows no increased focal uptake confirming the suspicion of an artifact.



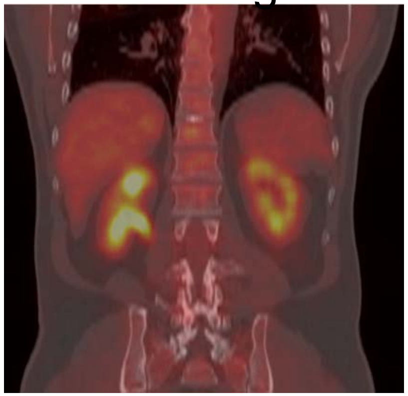
Use of software fusion in PET/CT

Whereas PET/CT may provide a very good overall (rigid) registration, differences between PET and CT (due to e.g. respiration, peristalsis) can persist.

original image



deformable registration



displacement map

Deformable registration procedures in particular can have utility in PET/CT if sufficient boundary conditions (or matched reference points) can be defined.

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MRI respiration image courtesy of Dr. D. Atkinson, Radiological Sciences & Medical Engineering Guy's Hospital, London UK.

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