PET/CT Attenuation Correction and Image Fusion

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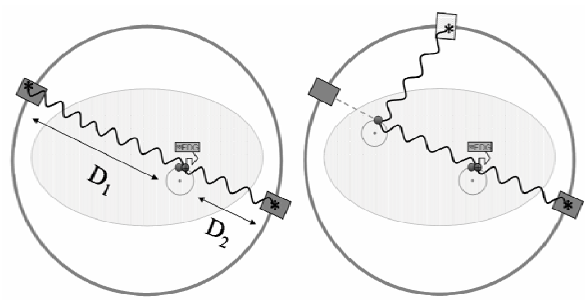
Part I – PET/CT Attenuation Correction

- PET images with and without AC
- Principles of CT-based AC
- Energy scaling and tissue characteristics
- Optimized kVp dependent scaling
- Respiration artifacts & protocols
- Metal artifacts and CT contrast agents
- Cardiac PET/CT applications

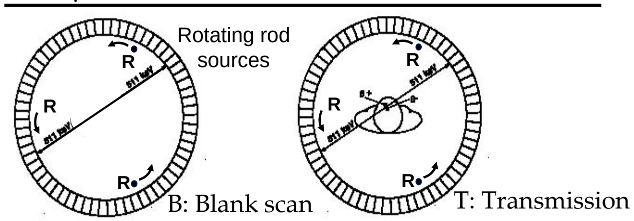
Emission signal attenuation



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 using 511 keV rod sources make a 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.

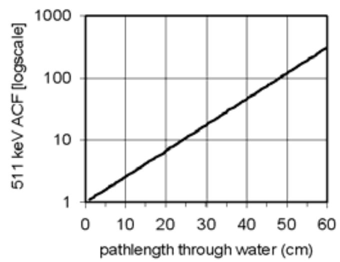
Attenuation correction factors for pathlengths through water:

$$\mathrm{ACF(LOR)} = e^{\int_{LOR} \mu(x)_{511\mathrm{keV}} dx}$$

$\mu(x)$ is the linear attenuation

Typical ACF values though tissue:

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

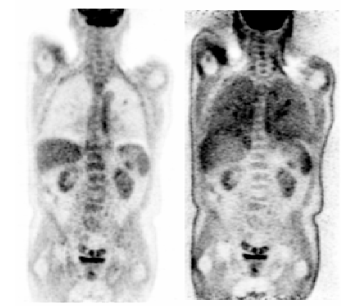


Attenuation correction - PET images

Can reconstruct PET images with or without attenuation correction

With attenuation correction

Without attenuation correction



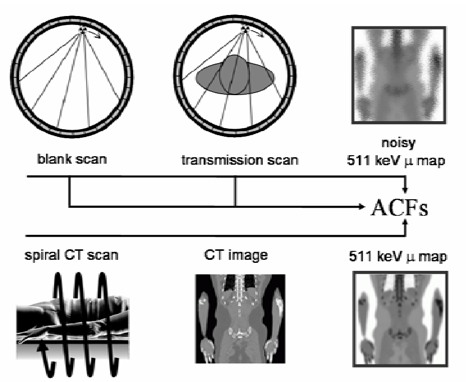
Features (non AC):

- 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

Principles of CT-based attenuation correction

Transmission based

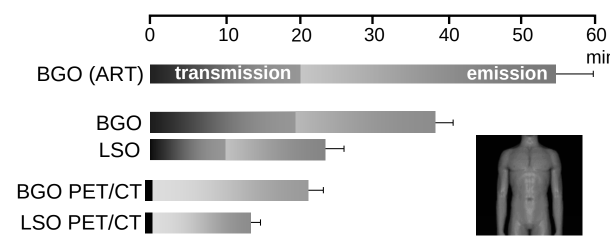
CT based



Progression of clinical whole-body scan times

CT-based AC obviates the need for a transmission scan

⇨ faster total scan times



CT images - what are they?

CT scanners "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

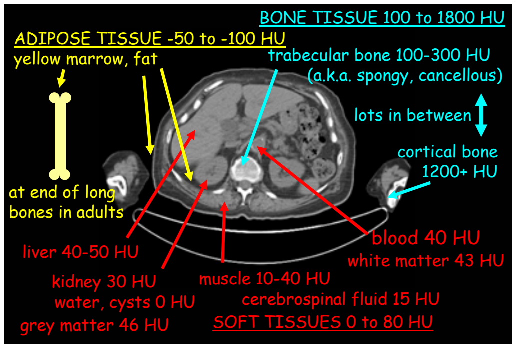
CT number uniformity:

0 HU $\pm$ 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.

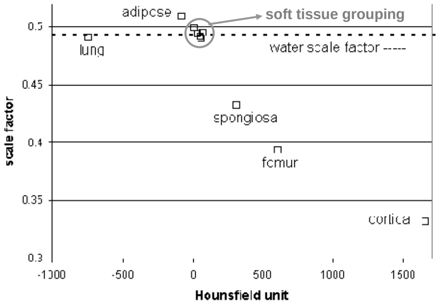
Hounsfield units of human tissues



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

Tissue characteristics: energy scaling CT ➡ PET

μ (511 keV) = μ (CT) x scale_factor



soft tissues all similar, bone scale factors lower

data based on ICRP 1975 tissue chemical compositions

Scaling algorithms

Threshold model:

Assume unique scale factor for each class of tissue separable by thresholding

(bone or soft tissue)

e.g. Kinahan et al, 1998

$$\mu^{PET} = 0.096\mathrm{cm}^{-1}\left(1 + \frac{HU}{1000}\right) \quad \text{for HU} < 300,$$

$$\mu^{PET} = 0.081\mathrm{cm}^{-1}\left(1 + \frac{HU}{1000}\right) \quad \text{for HU} > 300.$$

Mixing model:

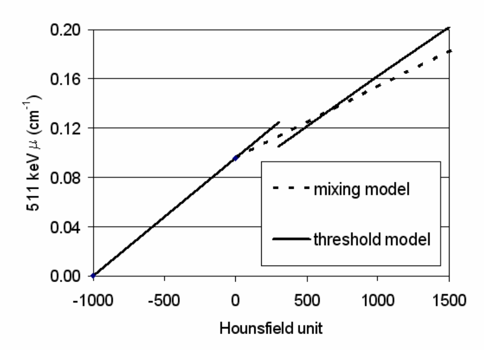
Assume variable mixtures of two well-defined substances, e.g. Burger et al 2002

For HU<0 as above,

For HU>0 (bone+water)

$$\left\{ \begin{array}{l} \mu^{PET} = \mu^{PET}_{water} + \mu^{CT}_{water}\left(\frac{HU}{1000}\right)\left(\frac{\mu^{PET}_{bone} - \mu^{PET}_{water}}{\mu^{CT}_{bone} - \mu^{CT}_{water}}\right), \\ \mu^{PET}_{water} = 0.096\mathrm{cm}^{-1}, \quad \mu^{PET}_{bone} = 0.172\mathrm{cm}^{-1}, \\ \mu^{CT}_{water} = 0.184\mathrm{cm}^{-1}, \quad \mu^{CT}_{bone} = 0.428\mathrm{cm}^{-1}. \end{array} \right.$$

Scaling algorithms

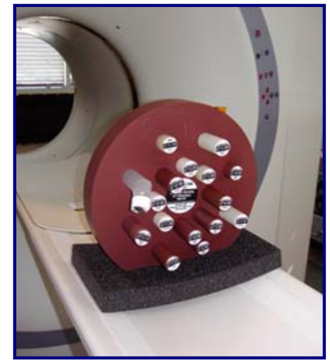


These methods as described not account for different kVp & make assumptions about the locations of thresholds and breaking points.

kVp dependent energy scaling

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

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



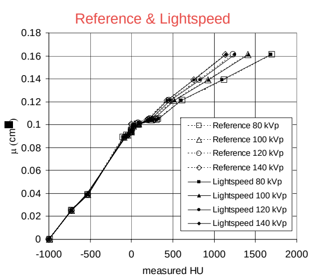
Transformation defined by measurements:

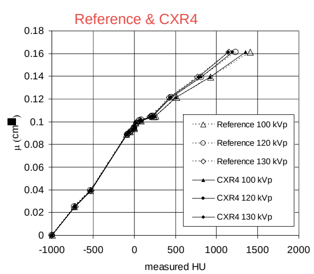
On a Siemens Sensation 16-slice CT at:

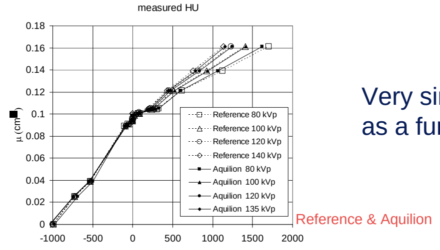
80, 100, 120, 140 kVp.

On a Siemens Emotion 6-slice CT at:

110, 130 kVp.

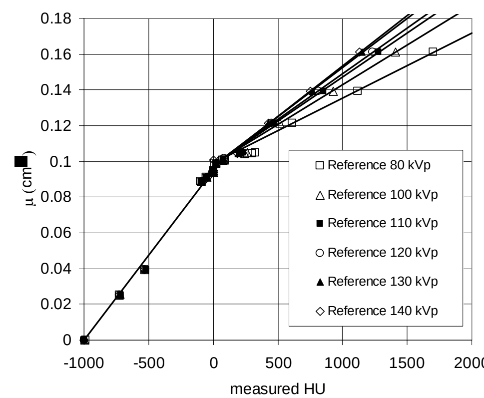






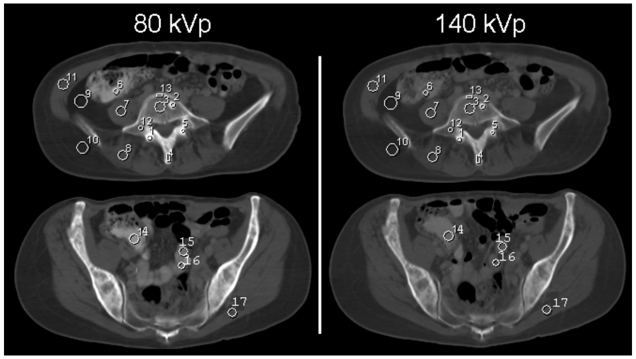
Very similar behavior as a function of kVp.

Bilinear kVp-dependent transformation

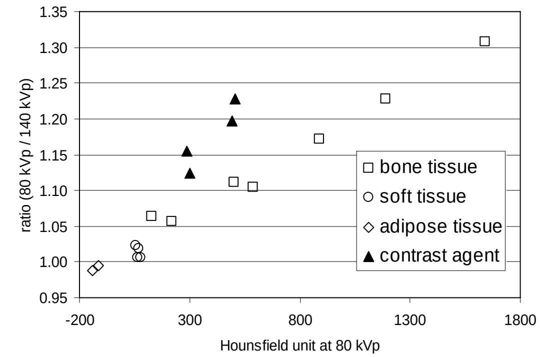


CT images: same patient at 80 kVp and 140 kVp

Define Regions of Interest (ROIs) for all tissues

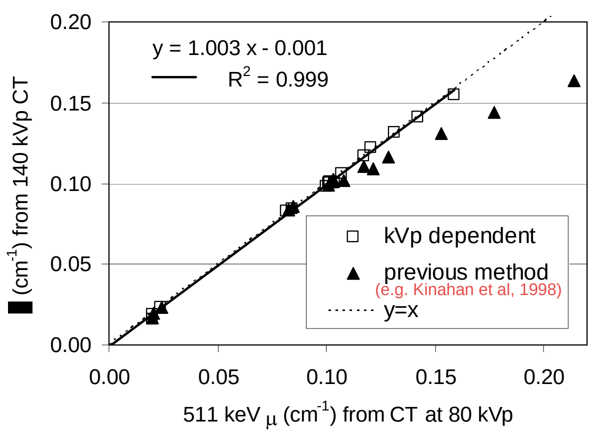


Dual-energy discrimination - HU ratio (80/140)



Can distinguish contrast agent from bone

Transformation of 80, 140 kVp CT into 511 keV μ



CT respiration protocols in PET/CT

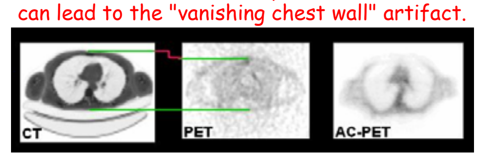
During the PET acquisition the patient is breathing shallowly - averaged over many cycles.

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.

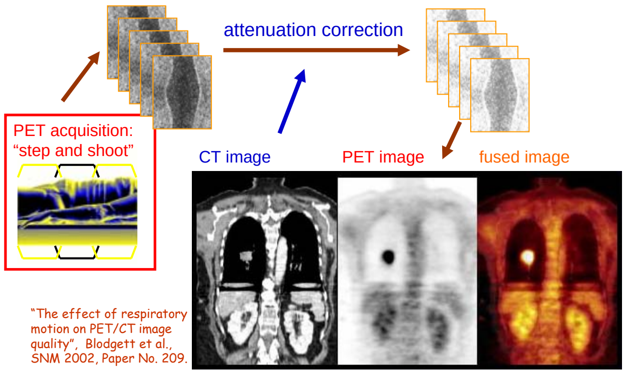


typical max. excursion:

deep ~10cm
shallow ~2cm

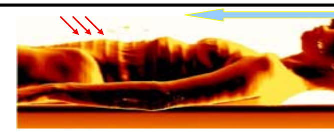
Respiration artifacts: propagation into PET

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



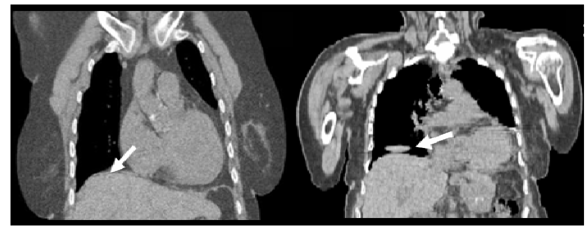
"The effect of respiratory motion on PET/CT image quality", Blodgett et al., SNM 2002, Paper No. 209.

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.

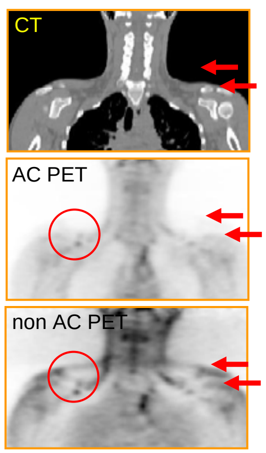
Other types of patient motion

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

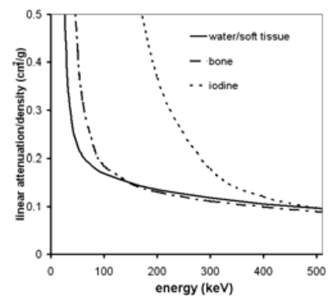
Example:

AC PET shows "shadowing" of focal uptake?

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



Properties of CT contrast agents



Contrast agent:

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

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

locally raises HU

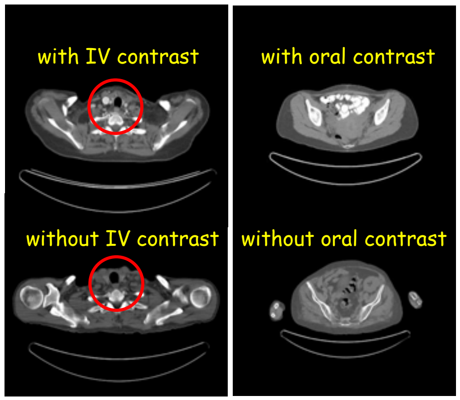
Oral contrast agent: dilute solution of barium sulphate or organically bound iodine is swallowed, generally well tolerated

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

Use of CT contrast agents

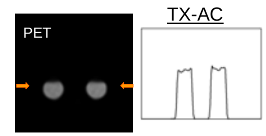
CT contrast agents can improve the diagnostic utility of the CT images.

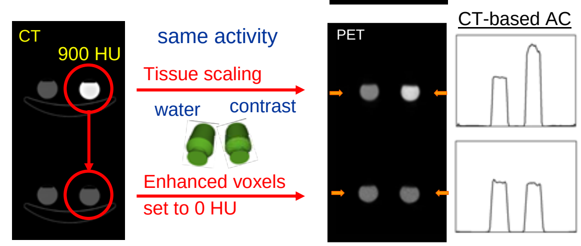
Do not affect PET except may introduce generally small biases through attenuation correction.



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.





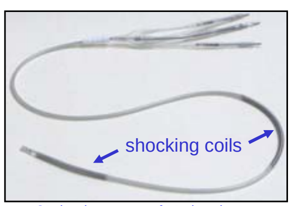
For typical values in patients (<900 HU) bias is generally modest. Will be larger in cases of contrast precipitation and IV bolus.

Cardiac PET/CT Implantable Cardioverter Defibrillators

Implantable cardioverter defibrillators (ICDs) are used to treat heart rhythms that are abnormally fast and life threatening, and they are becoming ever more prevalent.

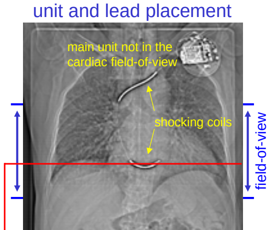
It is the shocking coils in the ICD leads that are most opaque to x-rays, leading to artifacts in the CT images that can then cause artifacts in the attenuation-corrected PET images.

The defibrillator unit itself is also highly opaque, but it is not proximate to the heart.

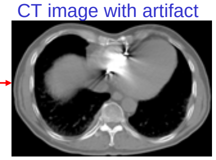


ICD lead courtesy of Medtronic, Inc.

Topogram showing ICD unit and lead placement

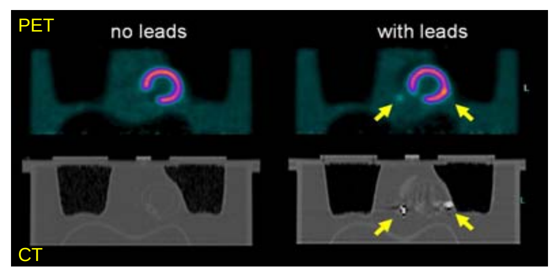


CT image with artifact



Phantom experiment

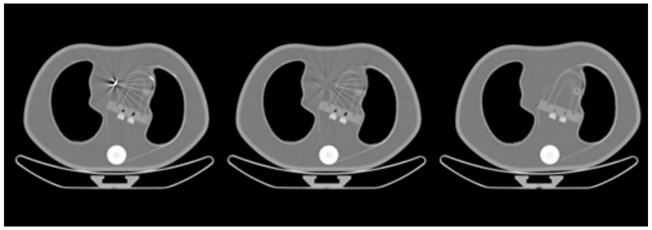
A cardiac insert filled with FDG activity was placed in a thoracic phantom containing a lower background activity (6:1 ratio approx). The phantom was imaged using a 16 slice LSO PET/CT (CPS Innovations) with and without ICD leads wrapped around the cardiac insert.



Artifactual elevated uptake is seen in the vicinity of the shocking coils in the leads. In the case of the coils being close to simulated myocardial uptake, the myocardial uptake pattern is significantly altered.

Application to phantom CT images

with leads | with leads, corrected | no leads



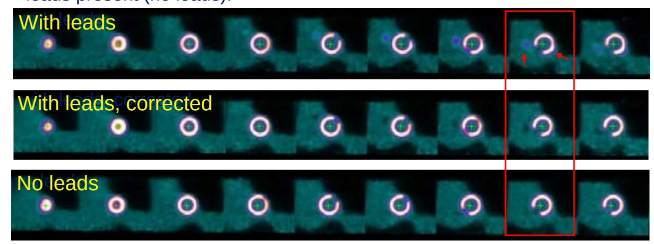
axial presentation

sagittal presentation

Phantom PET images: corrected images

The phantom acquisition with the leads present was reconstructed using the usual CT images (with leads) and using the corrected CT images (with leads, corrected).

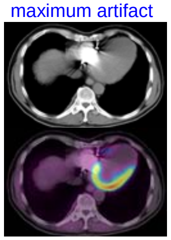
The attenuation-corrected PET images obtained were compared in short axis (SA) presentation with the corresponding acquisition without the leads present (no leads).



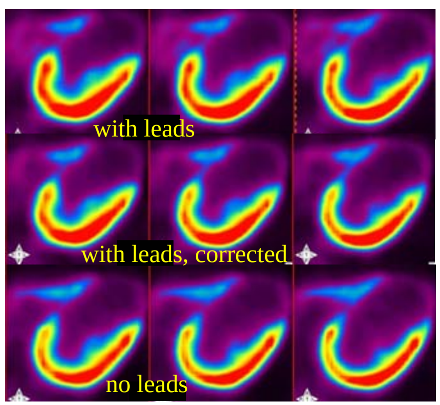
Improved correspondence is seen between the images without the leads and those using the corrected CT images in the presence of the leads.

Clinical study: myocardial uptake

maximum artifact



10% elevation seen due to leads without the correction applied.



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

Alpha Blending: method for fused display of two (color) images

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

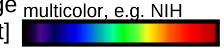
COLOR TABLES

inverse greyscale

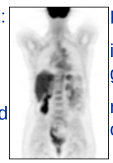
greyscale

blackbody

multicolor, e.g. NIH



CT image: greyscale report Hounsfield units



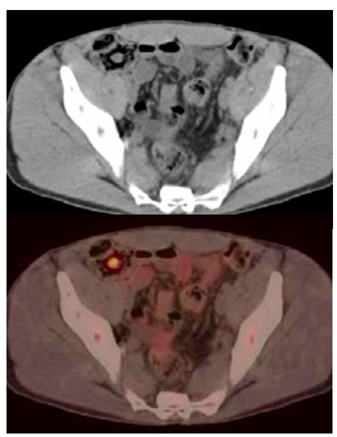
PET image: inverse greyscale report SUV or bq/ml

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

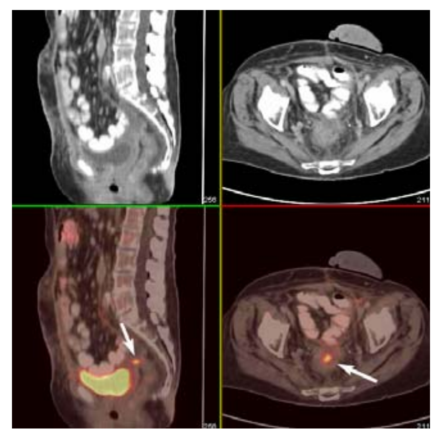
Localization advantages of PET/CT - example 1



incidental finding in right pelvis on PET

correlation with CT shows focus within right colon

Localization advantages of PET/CT - example 2



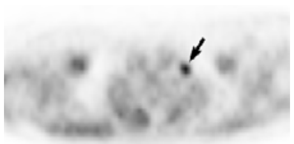
Ovarian cancer:

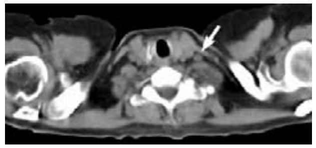
CT shows post surgical changes in the pelvis

PET reveals focal uptake at surgical site - suspicious for tumor

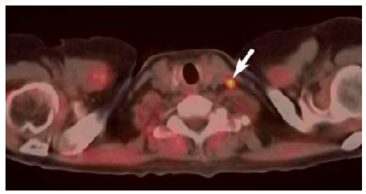
Localization advantages of PET/CT - example 3

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

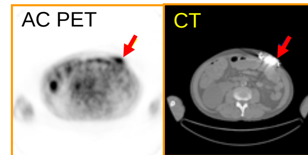


Interpretation of artifacts in fused images

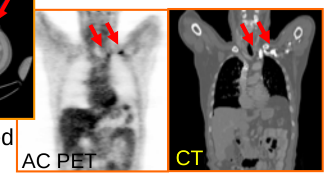
Tissue scaling of non-tissue high H.U. features in the CT images can lead to artifactual increased focal uptake.

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

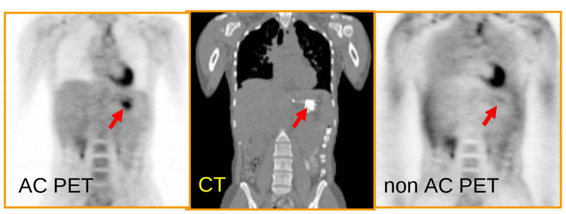


IV contrast bolus artifact

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.

Misc. References

General

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