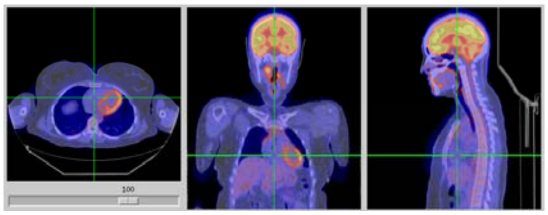
PET/CT Issues:
CT-based attenuation correction (CTAC), Artifacts, and Motion Correction



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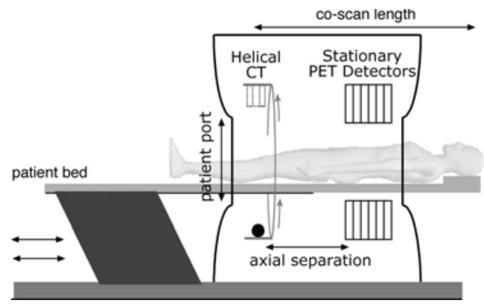
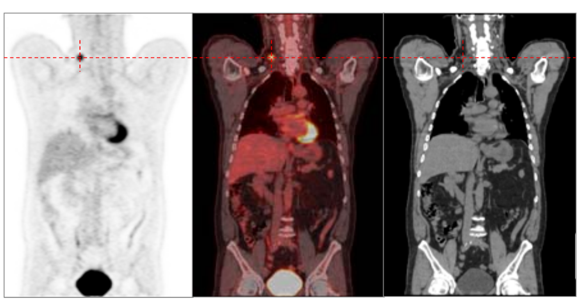
PET/CT Scanner Anatomy



All 3 (couch, CT and PET) must be in accurate alignment

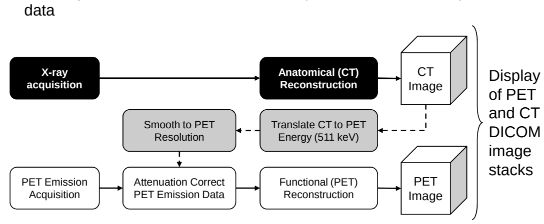
Imaging FDG uptake (PET) with anatomical localization (CT) and CT-based attenuation correction



Function | Function+Anatomy and CT-based attenuation correction | Anatomy

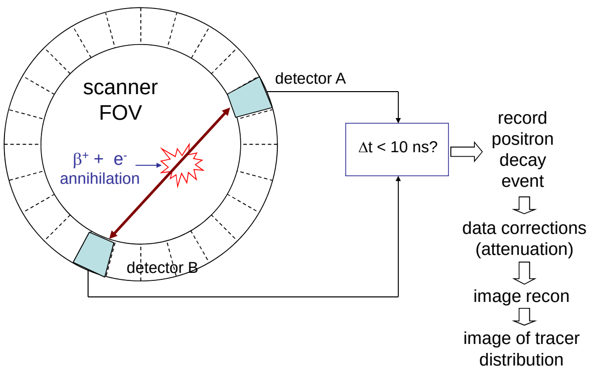
Data flow for data processing

- CT images are also used for calibration (attenuation correction) of the PET data



- Note that images are not really fused, but are displayed as fused or side-by-side with linked cursors

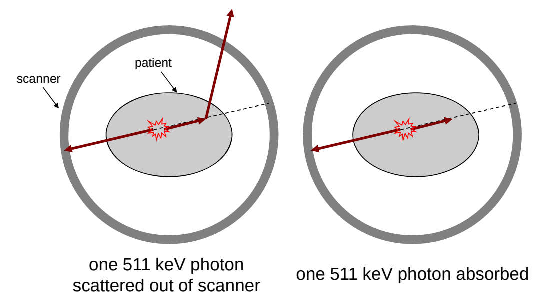
How it works: Timing coincidence



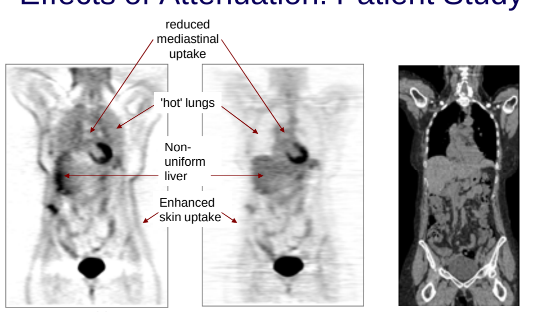
What is Attenuation?

The most important physical effect in PET imaging:

- The number of detected photons is significantly reduced compared to the number of source photons in a spatially-dependent manner
- For PET it is mainly due to Compton scatter out of the detector ring
- For CT it is a combination of Compton scatter and photoelectric absorption



Effects of Attenuation: Patient Study

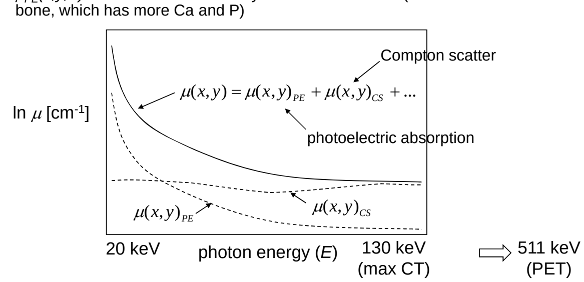


PET: without attenuation correction — PET: with attenuation correction (accurate) — CT image (accurate)

Energy dependence of attenuation

Typical energy dependence of attenuation for biological materials

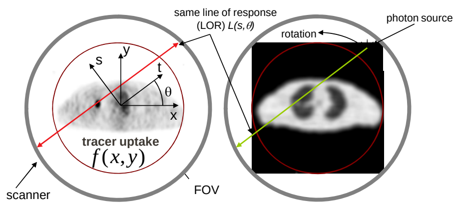
- $\mu_{CS}(x,y,E)$ is related to density
- $\mu_{PE}(x,y,E)$ is related to both density and atomic number (thus clear distinction of bone, which has more Ca and P)



- at the PET energy of 511 keV basically all Compton scatter interactions

Attenuation Correction for PET

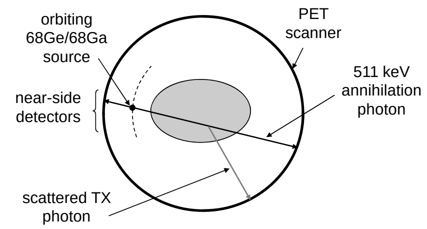
- Transmission scanning with an external 511 keV photon source can be used for estimation of attenuation in the emission scan
- The fraction absorbed in a transmission scan, along the same line of response (LOR) can be used to correct the emission scan data
- The transmission scan can also be used to form an attenuation image



Emission scan (EM) inverse gray scale

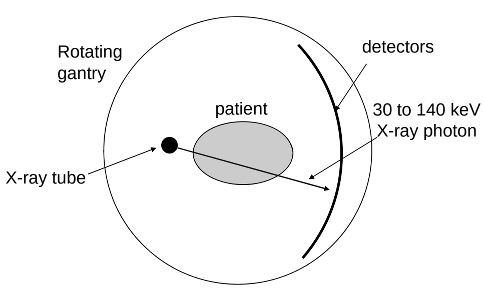
Attenuation (AT) gray scale

PET Transmission imaging (annihilation photon imaging)



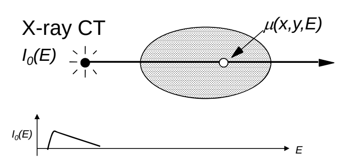
- Using 3-point coincidences, we can reject TX scatter
- $\mu(x,y)$ is measured at needed value of 511 keV
- near-side detectors, however, suffer from deadtime due to high countrates

But if you have PET/CT scanner: X-ray CT transmission imaging



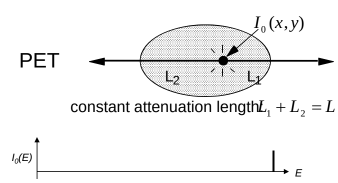
How can we use the CT data for CT-based attenuation correction (CTAC)?

Comparing X-ray and PET



$$I = \int_0^{\infty} \left(I_0(E)\, e^{-\int_0^L \mu(x.y,E)\, dL} \right) dE$$

Attenuation only, but with complicated energy weighting of source intensity and material-specific absorption



constant attenuation length $L_1 + L_2 = L$

$$I = \underbrace{\left(\int_{-\infty}^{\infty} I_0(x,y)\, dL \right)}_{\text{emission (sinogram) data}} \cdot \underbrace{\left(e^{-\int_{-\infty}^{\infty} \mu(x.y,511keV)\, dL} \right)}_{\text{attenuation factors}}$$

Uncoupled mono-energetic emission and material-specific absorption

Monoenergetic Imaging

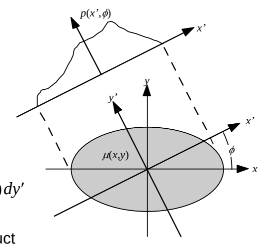
- For an ideal narrow beam of monoenergetic photons

$$I(x',\phi) = I_0 \exp\left(-\int_{-\infty}^{\infty} \mu(x,y,E_0)\,dy'\right)$$

- By taking the log of the relative transmission we have

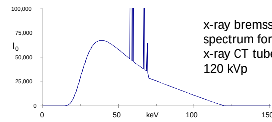
$$p(x',\phi) = \ln\left(\frac{I_0}{I(x',\phi)}\right) = \int_{-\infty}^{\infty} \mu(x,y,E_0)\,dy'$$

- From this we can accurately reconstruct $\mu(x,y,E_0)$ using filtered-backprojection



X-ray CT Scanning

- What do we measure with x-ray CT?
- Due to the *bremsstrahlung* spectrum from the x-ray tube we have a complicated weighting of measurements at different energies



x-ray bremsstrahlung energy spectrum for a commercial x-ray CT tube operated at 120 kVp

- The reconstructed image μ does not represent a specific physical quantity and can vary with kVp and object
- For this reason CT images are scaled to 'Hounsfield Units' (H) to allow comparisons, with air = -1000 and water = 0

$$H(x,y) = 1000\left(\frac{\hat{\mu}(x,y)}{\mu_{\text{water}}} - 1\right)$$

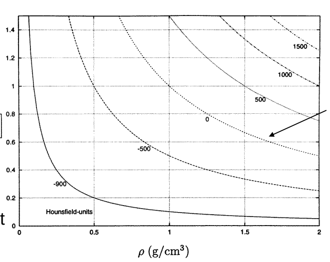
Effect of Polyenergetic Imaging

- A measured CT number can be invariant for changes in density vs atomic properties

$$\frac{1}{\bar{\mu}_{H_2O}} N_A \sum_{i=1}^{n} \left[\frac{w_i}{A_i}\bar{\sigma}_i\right]$$

(cm³/g)

Atomic properties (independent of density)

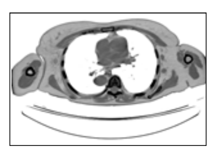


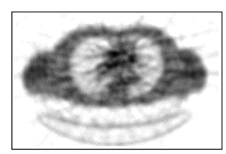
Constant CT number of 0 HU

density

Schneider et al. PMB 2000

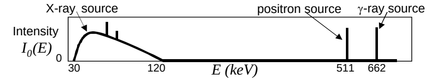
Comparison of transmission scan methods





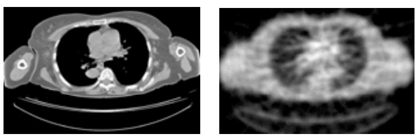
X-ray CT TX
- 1 s acquisition
- ~30 to 120 keV
- no quantitation
- lowest noise
- high contrast
- not affected by FDG activity in patient

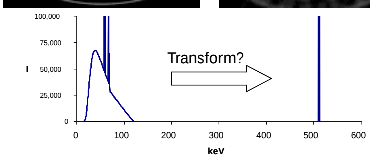
PET TX
- 3-5 min acquisition
- 511 keV
- accurate quantitation
- highest noise
- low contrast
- affected by FDG activity in patient



X-ray and Annihilation Photon Transmission Imaging for Attenuation Correction

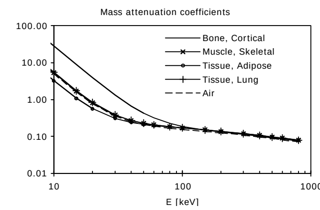
X-ray (~30-120 keV)	**PET Transmission** (511 keV)
Low noise	Noisy
Fast	Slow
Potential for bias when scaled to 511 keV	Quantitatively accurate for 511 keV





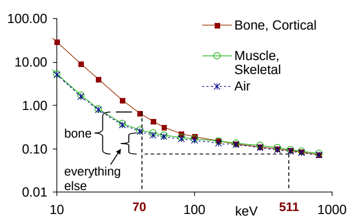
Mass attenuation coefficient

- Linear attenuation coefficients are expressed in units of inverse centimeters (cm^{-1}) and the Compton component is proportional to the density of the absorber
- It therefore is common to express the attenuation property of a material in terms of its mass attenuation coefficient μ/ρ in units of cm^2/g
- Thus the mass attenuation coefficient due to Compton scatter is approximately constant
- The mass attenuation coefficient for photoelectric absorption varies approximately as $\mu / \rho \propto Z^{4.5} / E^3$
- For higher energies and/or lower atomic numbers the mass attenuation coefficient is approximately constant



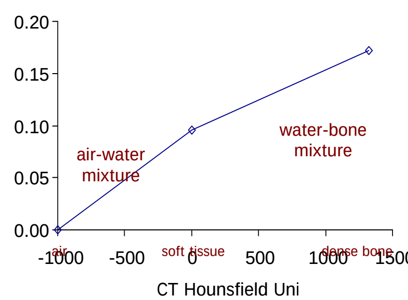
CT-based Attenuation Correction

- The mass-attenuation coefficient (μ/ρ) is remarkably similar for all non-bone materials since Compton scatter dominates for these materials. Bone has a higher photoelectric absorption cross-section due to presence of calcium
- Can used two different scaling factors: one for bone and one for everything else



CT-based Attenuation Correction

- Bi-linear scaling methods apply different scale factors for bone and non-bone materials
- Should be calibrated for every kVp and/or contrast agent



Density versus CT Number

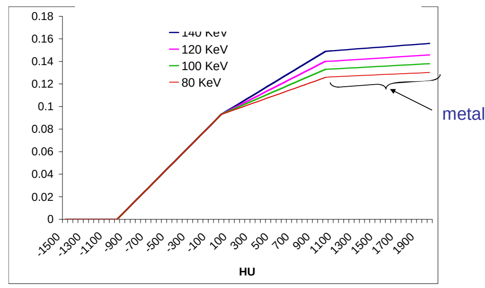
calculated densities vs CT number for 71 human tissues

QuickTime™ and a decompressor are needed to see this picture.

Schneider et al. PMB 2000

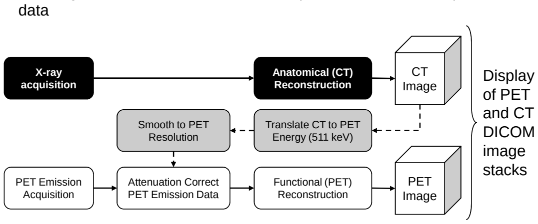
CT-based Attenuation Correction With Metals etc

- Clipping should be applied to CTAC correction factors to reduce artifacts from metal etc
- Curves should also be CT energy dependent



Data flow for data processing

- CT images are also used for calibration (attenuation correction) of the PET data



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Potential problems for CT-based attenuation correction with PET/CT

- Attenuation is the largest correction we apply to the PET data
- Artifacts in the CT image propagate into the PET image, since the CT is used for attenuation correction of the PET data
- Difference in CT and PET respiratory patterns
  - Can lead to artifacts near the dome of the liver unless motion compensation methods are used
- Contrast agents, implants, or calcium deposits
  - Can cause incorrect values in PET image unless correct CT-based attenuation correction tables are used
- Truncation of CT image
  - Can cause artifacts in corresponding regions in PET image unless wide-field CT image reconstruction is used - this should always be used by default
- Bias in the CT image due to beam-hardening and scatter from the arms in the field of view

PET and PET/CT Artifacts

PET-based errors
- Calibration problems
- Detector failures
- Resolution and partial volume effects
- patient motion

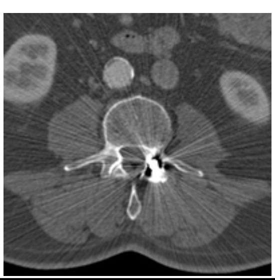
Errors from CT-based attenuation correction in PET/CT
- CT artifacts
- non-biological objects in patients
- respiratory mismatch between PET and CT images
- patient motion

Types of CT Artifacts

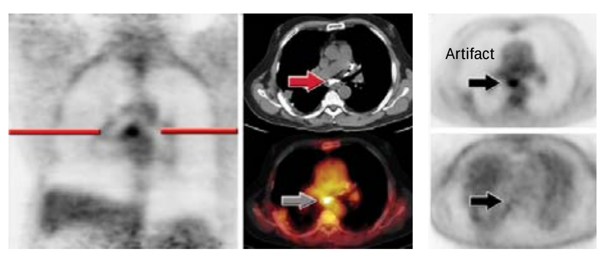
- Physics based
  - beam-hardening
  - partial volume effects
  - photon starvation
  - scatter
  - undersampling
- Scanner based
  - center-of-rotation
  - tube spitting
  - helical interpolation
  - cone-beam reconstruction
- Patient based
  - metallic or dense implants
  - motion
  - truncation

Metallic Objects

- Occur because the density of the metal is beyond the normal range that can be handled
- Additional artifacts from beam hardening, partial volume, and aliasing are likely to compound the problem



Calcified Lymph Node



Non-AC PET

Courtesy T Blodgett UPMC

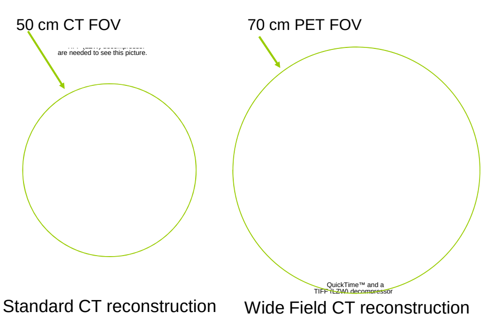
Metal Clip

Courtesy O Mawlawi MDACC

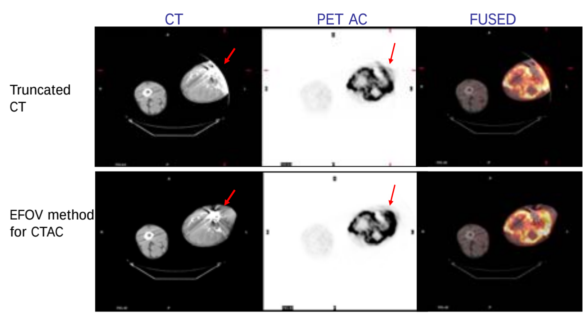
Truncation

- Standard CT field of view is 50 cm, but many patients exceed this
- Not often a problem for CT, but can be a problem when a truncated CT is used for PET attenuation correction

Removing CT Truncation Artifacts

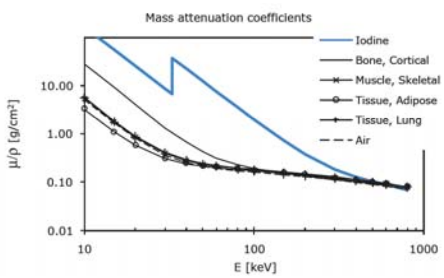


Truncation Artifacts and Wide-Field CT Methods



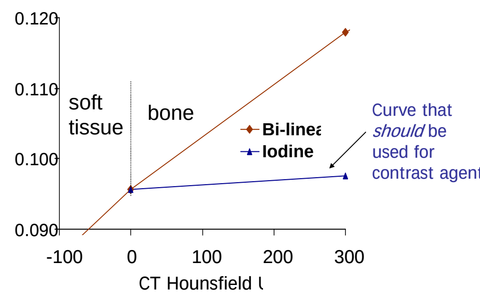
Max SUV changed from 3.4 to 12.7 with extended field of view CT

Effect of Contrast Agents



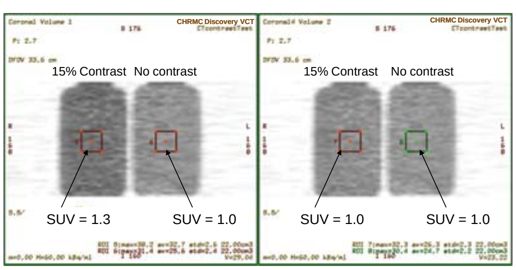
Effect of Contrast Agent on CT to PET Scaling

- The presence of Iodine confounds the scaling process as Iodine cannot be differentiated from bone by CT number alone.



Effect of contrast agent

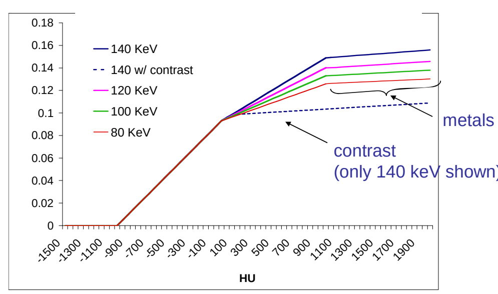
- FDG in 1 L water filled jugs
- True SUV = 1



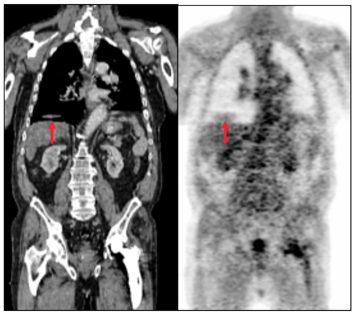
Without contrast agent correction With contrast agent correction

CT-based Attenuation Correction With Metals etc

- Clipping should be applied to CTAC correction factors to reduce artifacts from metal etc
- Curves should also be CT energy dependent



Breathing Artifacts: Propagation of CT breathing artifacts via CT-based attenuation correction



Attenuation artifacts can dominate true tracer uptake values

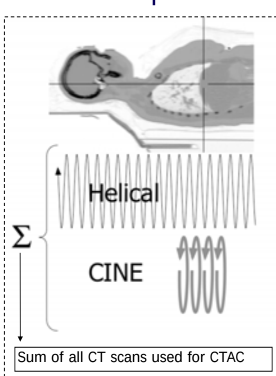
Patient and/or bed shifting

- Large change in attenuation at lung boundaries, so very susceptible to errors

PET image without attenuation correction | PET image with CT-based attenuation correction (used for measuring SUVs) | PET image fused with CT

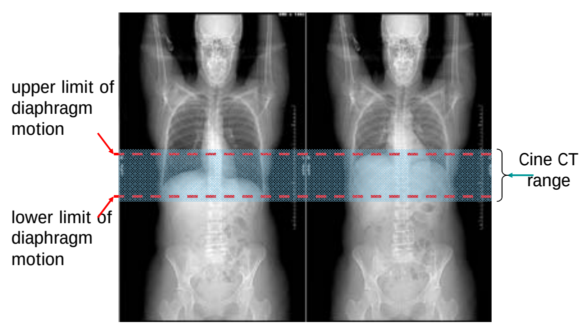
Helical+CINE CTAC Acquisition to Compensating For Patient Respiration

1. Standard non-contrast helical CT (diagnostic beam) for both CT imaging correlation and for CT-based attenuation correction (CTAC)
2. Cine CT acquired over the diaphragm region for respiratory motion (Pan et al. JNM 2005)
3. Average of helical+Cine CT acquired is used for CTAC of PET data



Helical+CINE CTAC Protocol

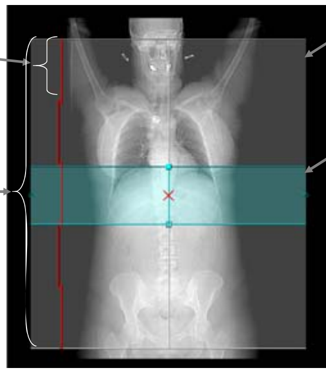
•Dual scout scans for diaphragm range determination



max inspiration max expiration

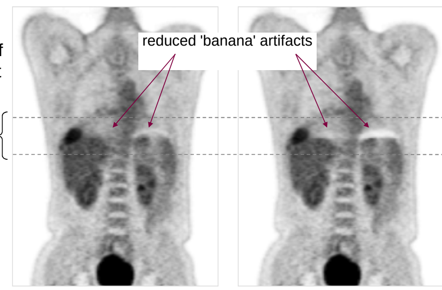
Helical+CINE CTAC Protocol

•Scan range definitions



Helical+CINE CTAC Protocol

•Effect on PET emission images



Summary

- Look at images with and without attenuation correction if in doubt
- Don't assume correct alignment *always* between PET and CT, at a minimum, patient and/or bed motion is a possibility
- Manufacturers have new methods to help with truncation and respiratory motion artifacts
- CT artifacts and dense objects can propagate errors into the PET image via CTAC
- CINE-CTAC method can help reduce respiratory-induced banana artifacts

REFERENCES

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- Bushberg, *The Essential Physics of Medical Imaging*, 2nd Edition, 2002
- Kalender WA, Radiology, 176(1):181-3, 1990
- Kinahan PE, Hasegawa BH, Beyer T. X-ray Based Attenuation Correction for PET/CT Scanners. Seminars in Nuclear Medicine. 33(3):166-79,2003