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

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**

- **$\Delta t < 10$ ns?**
- **scanner FOV**
- **$\beta^+ + e^- \text{ annihilation}$**
- **detector A**
- **record positron decay event**
- **data corrections (attenuation)**
- **image recon**
- **image of tracer distribution**

**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
  - $\mu_{\text{CS}}(x,y)\text{E}$ is related to density
  - $\mu_{\text{PE}}(x,y)\text{E}$ 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.

**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.

**Comparing X-ray and PET**

- X-ray CT

  $$I = \int I_0(x,y) e^{-\mu(x,y)\cdot dL}$$

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

- PET

  $$I = \left\{ \int I_0(x,y) e^{-\mu(x,y)\cdot dL} \right\} e^{-\mu(x,y)\cdot L}$$

  Uncoupled mono-energetic emission and material-specific absorption.
Monoenergetic Imaging

- For an ideal narrow beam of monoenergetic photons
  \[ I(x', \phi) = I_0 \exp \left( -\int \mu(x, y, E) dy' \right) \]

- By taking the log of the relative transmission we have
  \[ p(x', \phi) = \ln \left( \frac{I_0}{I(x', \phi)} \right) = \int \mu(x, y, E) dy' \]

- From this we can accurately reconstruct \( \mu(x, y, E) \) 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

\[ I(x', \phi) = I_0 \exp \left( -\int \mu(x, y, E) dy' \right) \]

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

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

Effect of Polyenergetic Imaging

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

\[ \frac{1}{\rho_{\text{water}}} \sum_{A} N_{A} \left( \frac{\mu_{A}(\rho)}{\mu_{\text{water}}} \right) \]

Atomic properties (independent of density)

\[ \rho \text{ (g/cm}^3) \]

\[ \text{density} \]

Constant CT number of 0 HU

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

\[ E \text{ (keV)} \]

Intensity

\[ I_j(E) \]

\[ E \text{ (keV)} \]

\[ \gamma \text{-ray source} \]

\[ \text{ positron source} \]

\[ \text{X-ray source} \]
X-ray and Annihilation Photon Transmission Imaging for Attenuation Correction

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

Low noise Noisy
Fast Slow

Potential for bias when scaled to 511 keV

CT-based Attenuation Correction

- The mass-attenuation coefficient ($\mu/\rho$) 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

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 ($\mu/\rho$) in units of cm²/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

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

Mass attenuation coefficients

- Bone, Cortical
- Muscle, Skeletal
- Tissue, Adipose
- Tissue, Lung
- Air

Transform?

Bone
Muscle
Skeletal
Air

CT Hounsfield Unit

- air-water mixture
- water-bone mixture
Density versus CT Number

calculated densities vs CT number for 71 human tissues

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

PET Emission Acquisition

PET Emission Data

Attenuation Correct PET Emission Data

Functional (PET) Reconstruction

CT Image

Display of PET and CT DICOM image stacks

X-ray Acquisition

Anatomical (CT) Reconstruction

Spectra to PET Resolution

Transmission CT to PET (Energy 101 keV)

PET Image

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 splitting
  - 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
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

50 cm CT FOV
70 cm PET FOV

Standard CT reconstruction
Wide Field CT reconstruction

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

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

Effect of Contrast Agent on CT to PET Scaling

- Mass attenuation coefficients
- CT Hounsfield Greenwich.
- U

Curve that should be used for contrast agent

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

metals

contrast (only 140 keV shown)
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

Sum of all CT scans used for CTAC
Helical+CINE CTAC Protocol

- Scan range definitions

1. CT helical range
2. CT cine range
3. Single PET bed range
4. Total PET range for 5 bed positions

Helical+CINE CTAC Protocol

- Effect on PET emission images

- Area of impact
- Reduced 'banana' artifacts

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