PET/CT simulation for radiation therapy applications

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Outlines
- Challenges in PET/CT for RT
- Dose efficiency of single slice CT and multi-slice CT
- Radiation dose in PET/CT
- Spatial and temporal resolution
- Free breathing vs breath hold protocol
- Potential misregistration in the thorax
- 4DCT, MIP CT and Average CT
- Clinical examples
- Summary

Evolution of PET/CT

<table>
<thead>
<tr>
<th>Year</th>
<th>PET/CT Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>Partial ring (68Ge)</td>
</tr>
<tr>
<td>1998</td>
<td>Full ring (68Ge)</td>
</tr>
<tr>
<td>1999</td>
<td>Full ring (68Ge)</td>
</tr>
<tr>
<td>2000</td>
<td>BGO PET/CT</td>
</tr>
<tr>
<td>2001</td>
<td>LSO PET/CT</td>
</tr>
<tr>
<td>2002</td>
<td>LSO 16 PET/CT</td>
</tr>
<tr>
<td>2003</td>
<td>Panel PET/CT</td>
</tr>
</tbody>
</table>

Source: Townsend et al. JNM 2004;45:11

Major PET/CT components

- CT Gantry
- Add Table
- Add Carriage/Base Plate
- Add PET Ring and Electronics
- Add Source Loader Assembly & Cal Ring

GE Healthcare
**PET/CT systems**

- **GE**
  - Discovery LS (BGO, 2D/3D, CT: 4/8/16-slice, 0.5 sec)
  - Discovery ST (BGO, 2D/3D, CT: 4/8/16-slice, 0.5 sec)
  - Discovery DSTE (BGO/LSO, 2D/3D, CT: 16, 0.5 sec)
  - Discovery DVCT (BGO/LSO, 2D/3D, CT: 64, 0.35 sec)

- **Philips**
  - Gemini (GSO, 3D, CT: 6-slice, 0.4 sec)
  - Gemini (GSO, 3D, CT: 10-slice, 0.4 sec)
  - Gemini (GSO, 3D, CT: 16-slice, 0.4 sec)
  - Gemini-TF (LYSO, 3D, CT: 16/64-slice, 0.4 sec)

- **Siemens**
  - Biograph 2 (LSO, 3D, CT: 2-slice, 0.8 sec)
  - Biograph 6 (LSO, 3D, CT: 6-slice, 0.6 sec)
  - Biograph 16 (LSO, 3D, CT: 16-slice, 0.42 sec)
  - Biograph 40 (LSO, 3D, CT: 40-slice, 0.37 sec)
  - Biography 64 (LSO, 3D, CT: 64-slice, 0.33 sec)

**Differences btw PET and CT**

- **PET or PET/CT (functional)**
  - PET spatial resolution ~ 5-8 mm
  - PET temporal resolution ~ 3 mins or breathing cycle(s) 4-6 s
  - Wall motion assessment and ejection fraction with cardiac gating (4D-PET)
  - Tumor motion imaging with respiratory gating (4D-PET)

- **CT (anatomical)**
  - CT spatial resolution in Z ~ 0.6 to 2.5 mm
  - CT spatial resolution in plane ~ 0.4 to 0.6 mm
  - CT temporal resolution ~ 125 ms to 4 s
  - Coronary artery imaging with cardiac gating (Cardiac-CT)
  - Tumor motion imaging with respiratory gating (4D-CT)

**Challenges of PET/CT in RT**

- Reimbursement
- PET/CT is mostly in Nuclear Medicine
- Diagnosis and staging in Nuclear Medicine
- Treatment planning in Radiation Therapy
- Training of personnel
- More charge for diagnostic PET/CT than for treatment planning CT
- SUV not reproducible from Nuc. Med. to RT
- No standard for GTV delineation of PET volume
- Location, location and location (not perfect in the thorax)

**Tool for tumor contouring with SUV**

- GE Advantage Windows
- Pinnacle Planning System
Multi-slice CT: detector

- Scintillator: Converts X-rays to light
- Photo Diode Array: Converts light to electrical signal
- Connector: Carries signal to DAS

Multi-slice CT high temporal resolution

Advances in CT
- Step-and-shoot (S&S) CT
- Helical CT (1989)
- 4-slice CT (1998) plus 0.5 s rotation
- 8-slice CT (2000)
- 16-slice CT (2002)
- 64-slice CT (2004)
- Dual detector & x-ray tube CT (2005)
- 256-slice CT (2006)
- 320-slice CT (2007)

Selection of PET/CT
- 16-slice PET/CT
  - Oncology application
  - If not 16-slice, then go for 8-slice
- 16-slice PET/CT
  - Cardiology application without coronary artery CT imaging
- 64-slice PET/CT
  - Cardiology application with coronary artery imaging
  - Perfusion CT imaging
**Dose efficiency: SSCT > MSCT**

- Single Slice Detector
  - 100% of beam utilized
- Unused X-ray penumbra
  - 66% of beam utilized (4x1.25)
- Larger collimation is more dose efficient!

- 97% of beam utilized (4x5)

**Coronary artery imaging**

**Radiation dose**

- FDG dose: 10.73±3.48 mSv with 10 mCi injection and 70 kg body weight (Deloar et al, EJNM 1998; 25:565-674)
  - 1.1 mSv/mCi

- CT dose: 16.2 mSv @120 kV, 300 mA, 0.5 s, 16x1.25 mm, pitch 1.375,100 cm
  - CT dose ~ (mA x s) / Pitch with same x-ray collimation
    - Technique 1
      - 300 mA, 0.5 s, 1.375 pitch (300*0.5/1.375)=109 mAs
    - Technique 2 (2.4 times the technique 1)
      - 380 mA, 0.8 s, 0.938 pitch (380*0.8/0.938)=256 mAs
  - Dose efficiency:
    - 66% for 4x1.25 mm
    - 81% for 8x1.25 mm
    - 97% for 16x1.25 mm

- CT dose: 13 mSv @120 kV, 300 mA, 0.5 s, 16x1.25 mm, pitch 1.375, and noise index=20

**Pediatric CT Protocol for PET/CT**

<table>
<thead>
<tr>
<th>Age</th>
<th>kVp</th>
<th>mA</th>
<th>% adult dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-18 mos</td>
<td>100</td>
<td>60</td>
<td>14%</td>
</tr>
<tr>
<td>1.5-4 yrs</td>
<td>100</td>
<td>70</td>
<td>16%</td>
</tr>
<tr>
<td>5-7 yrs</td>
<td>100</td>
<td>90</td>
<td>21%</td>
</tr>
<tr>
<td>8-12 yrs</td>
<td>100</td>
<td>120</td>
<td>28%</td>
</tr>
<tr>
<td>12-17 yrs</td>
<td>120</td>
<td>110</td>
<td>37%</td>
</tr>
</tbody>
</table>

Adult protocol uses 120 kVp and 300 mA
Pediatric CT scans

5 yr old 1st scan
Scan is 30% dose of 1st scan

13 yr old 1st scan
Scan is 25% dose of 1st scan

Radiation Oncology PET/CT

Infrared Reflector
Infrared Camera
Flat Tabletop

4D-CT Protocol

- Cine scan
- 8 slices of 2.5 mm per rotation
- 0.5 sec sec/revolution
- 0.1 to 0.5 sec interval between reconstructions
- Scan duration = breathing cycle + 1 sec
- Synchronized with RPM (Real-time Position Management Gating System)
- Dose is 50 mGy for chest and < 75-100 mGy for abdomen

Cine 4DCT for 4/8/16/64-slice, and helical 4DCT for 16/64-slice
Detector configuration for 4D-CT

4D-CT Data Acquisition
**4D-CT**

- Respiratory tracking with Varian RPM optical monitor
- CT images acquired over complete respiratory cycles

Pan et al., Med Phys, 2004

**1st clinical case from MGH**

25 sec Cine scan (200 mA/s sec per step) with free breathing of 3.72 sec average breathing cycle

**4D-CT patient study (1)**
- Axial
- Coronal
- Sagittal

**4D-CT patient study (2)**
- Axial
- Coronal
- Sagittal
**Current PET/CT only matches spatial not temporal resolution between PET and CT**
Ring Artifacts in 120 kV not in 140 kV

Ring artifacts from CT

Ring artifacts at different window & levels

These are what PET sees
**Ring artifacts from CT**

- Ring artifact at 120 kV
- No ring artifact at 140 kV

**From PET-Transmission to CT**

- **Advance NXi PET scanner (Wu et al, EJNM 2004)**
  - Two rotating $^{68}$Ge (511 keV, T$_{1/2}$=287 days) rod sources
  - 20 rotations per min
  - 15.3 cm long and 4.0 mm in diameter
  - Maximum activity 370 MBq/rod (740 MBq total)
  - Acquisition time 5-15 min/bed
  - High noise and time consuming
  - 40 observations per location per minute in PET-Transmission

- **CT**
  - 1 observation per location in CT (0.5 to 1 s)
  - Low noise and quick, yet sometimes causing problems

**Differences between PET and CT**

- **PET**
  - scan of 15 cm for 3 to 6 mins,
  - spatial resolution ~ 5-8 mm
  - temporal resolution ~ breathing cycle

- **CT – 0.5 sec rotation**
  - scan of 90 cm < 20 sec
  - spatial resolution < 0.5 mm
  - temporal resolution < 1 sec

**Mis-matched PET-CT data sets**

- **Mismatch 1:**
  - CT diaphragm position lower than PET
- **Mismatch 2:**
  - CT diaphragm position higher than PET

Potential misalignment between PET and CT images
**PET/CT protocol**

- CT scout 80 kV 10 mA
- CT (helical)
  - 16 x 1.25 mm collimation, 120 kV, 300 mA, 0.5 sec, pitch 1.35 and auto dose
  - Dose ~7.5 mGy
- PET (2D) 3 min/bed (15 to 20 mCi) and 6 beds (15 cm/bed)

3 mins per patient

**Breath-hold or free-breathing in CT?**

**Misalignment in breathing states**

Pan et al, JNM, 2005

**Freq. of misalignment in 100 patients @ BH**

Pan et al, JNM, 2005
Breathing Artifacts

Protocol: 16x0.625 mm, 0.8 s gantry rotation; pitch 1.375:1
Speed: 13.75 mm/0.8 s or 17.2 mm/s

Breathing artifacts to physiological info

Breath cycle = 80.3/(13.75/0.8) = 4.67 s
Heart rate = (21/(13.75/0.8)) -1*60 = 49 bpm

Average CT (ACT)

Slow CT ≠ Average CT
Long slow scan ≠ Long fast scan

Average CT for dose calculation, proton plan and IGRT

Basic CT scan modes

Axial (Step and shoot)
one rotation (≤ 4 s)
one rot.(≤ 2 s for 64-slice)
Helical
pitch 0.5 to 1.5

Pitch: table translation per rotation
X-ray beam width
### Basic CT scan modes

<table>
<thead>
<tr>
<th>Axial (Step and shoot)</th>
<th>Axial (step and shoot) (low dose cardiac, CACS)</th>
<th>Cine (4DCT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>one rotation (&lt;= 4 s)</td>
<td>2-3 rotation</td>
<td>multiple rotations</td>
</tr>
<tr>
<td>1 rotation (&lt;= 2 s for 64-slice)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helical</td>
<td>5 Helical (cardiac)</td>
<td>$5$ Helical (4DCT)</td>
</tr>
<tr>
<td>pitch 0.5 to 1.5</td>
<td>pitch 0.2 to 0.3</td>
<td>pitch &lt; 0.1</td>
</tr>
</tbody>
</table>

Pitch = $\frac{\text{table translation per rotation}}{\text{X-ray beam width}}$

### Slow scan CT artifacts

- 0.5 sec rotation
- 4 sec rotation

Average CT (4 sec) vs Slow CT (4 sec)

### Average CT is better than slow CT

(2 adjacent CT slices of 2.5 mm apart)

- 4-s slow CT
- Average CT

### High radiation dose with cine CT?

- 60 mAs & 1.2 mSv
**Cine CT averaging**

1. **X-ray on/off**
   - **Cine CT Images**
     - 1st table position (0-3 cm)
     - 2nd table position (3-4 cm)
     - 3rd table position (4-5 cm)

2. **Helical CT**
   - **Combined helical and respiration averaged CT**
     - **Averaging CT**

**PET/CT + Average CT**

- **CT scout** 80 kV 10 mA
- **CT (helical)**
  - 16 x 1.25 mm collimation, 120 kV, 300 mA, 0.5 sec, pitch 1.35 and auto dose
  - Dose ~7.5 mGy
- **PET (2D)** 3 min/bed (15 to 20 mCi) and 6 beds (15 cm/bed)
- Average CT from cine CT @ 5 mGy

**Clinical Data**
Clinical Studies

Mismatch 1: CT diaphragm position lower than PET

Mismatch 2: CT diaphragm position higher than PET

Mismatch 3: CT diaphragm position lower than PET

Mismatch 4: CT diaphragm position lower than PET

+57%

Patient study #1

SUV=10.8

SUV=13.7 (+27%)
Patient study #3

FDG uptake in the liver?

FDG uptake in the kidney

Lung lesion or liver lesion?
Lung lesion or liver lesion?

PET/CT scan indicated a positive response to induction chemo with HCT. The patient had a negative response to the chemo with ACT.

Example from CGMH (Taipei)

Improve the restaging after chemo

PET/CT scan indicated a positive response to induction chemo with HCT.

Impact on treatment planning

Previous GTV was outlined based on CT and clinical PET without motion correction. New GTV was redefined based on the correct information from PET with ACT.
**Average CT in cardiac PET**

Pan et al., Med. Phys. 2006

**Heart motion in breath-hold**

250 msec temporal resolution

The heart does not seem to move in space during the breath-hold

**Cardiac and respiratory motion**

500 msec temporal resolution and 100 msec interval between reconstructions

**Table shifted between HCT and ACT**

HCT (correct table)  HCT (incorrect table)
Summary

- Challenges for PET/CT in RT
- PET/CT = PET/MSCT
- Cardiac CT is the main driving force for new MSCT
- 4D CT is important in PET/CT for radiation therapy
- Misregistration between CT and PET may be brought under control by average CT