PET/CT simulation for radiation therapy applications

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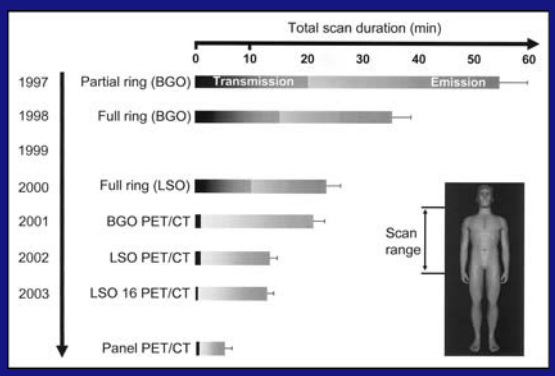
Outlines

- 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



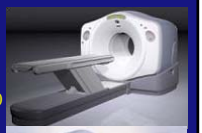
Townsend et al. JNM 2004;45(1)

Major PET/CT components

GE Health Care

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/LYSO, 2D/3D, CT:16, 0.5 sec)
  - Discovery DVCT (BGO/LYSO, 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)
  - Germini-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)



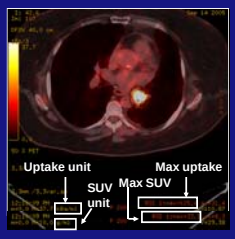
Differences btw PET and CT

- 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

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)

Cardiac CT

1 cm — S & S

Helical

2 cm

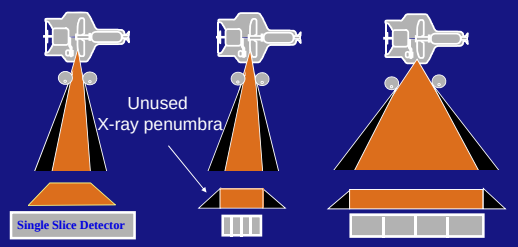
4 cm — Helical

16 cm — S & S

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

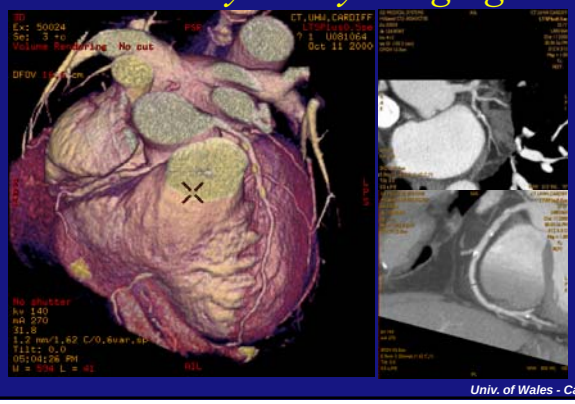
Dose efficiency: SSCT > MSCT



100% of beam utilized | 66% of beam Utilized (4x1.25) | 97 % of beam Utilized (4x5)

Larger collimation is more dose efficient!

Coronary artery imaging



Univ. of Wales - Cardiff

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 (http://www.internaldosimetry.com/freedosestimates/adult/linkedpages/f18FDG.html)
- 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)
      - 300 mA, 0.8 s, 0.938 pitch (300*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

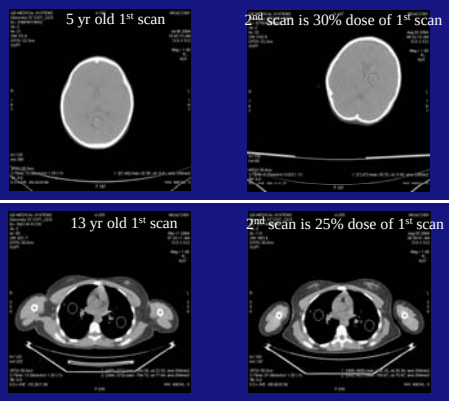
Pediatric CT Protocol for PET/CT

(0.5 sec, 8 x 1.25 mm collimation and 1.35 pitch)
(0.5 sec, 16 x 1.25 mm collimation and 1.375 pitch)

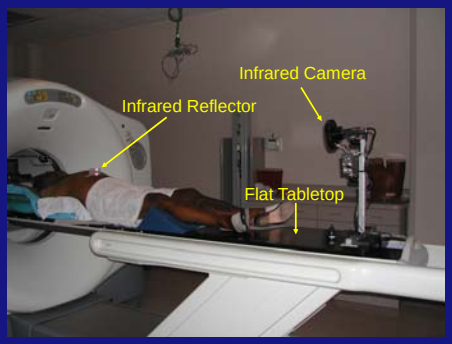
Age	kVp	mA	% adult dose (11.3 mGy)
0-18 mos	100	60	14%
1.5-4 yrs	100	70	16%
5-7 yrs	100	90	21%
8-12 yrs	100	120	28%
12-17 yrs	120	110	37%

Adult protocol uses 120 kVp and 300 mA

Pediatric CT scans



Radiation Oncology PET/CT



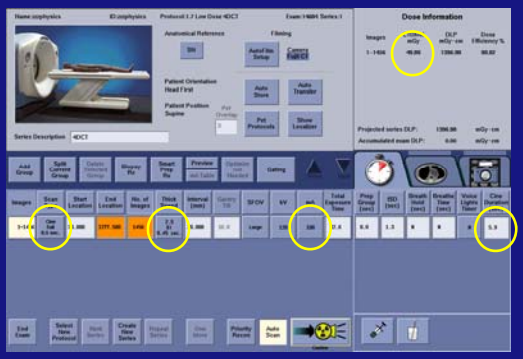
Courtesy of Peter Balter

4D-CT Protocol

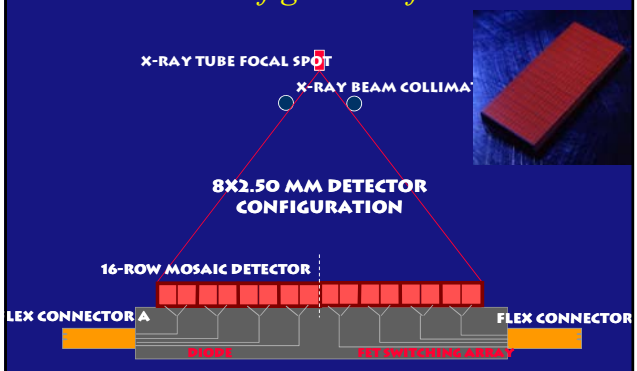
- Cine scan
- 8 slices of 2.5 mm per rotation
- 0.5 sec sec/revolution
- 0.1 to 0.5 sec interval between reconstructions
- Scan duration = breathing cycle + 1 sec
- Synchronized with RPM (Real-time Position Management Gating System)
- Dose is 50 mGy for chest and < 75-100 mGy for abdomen

Cine 4DCT for 4/8/16/64-slice, and helical 4DCT for 16/64-slice

Cine CT user interface

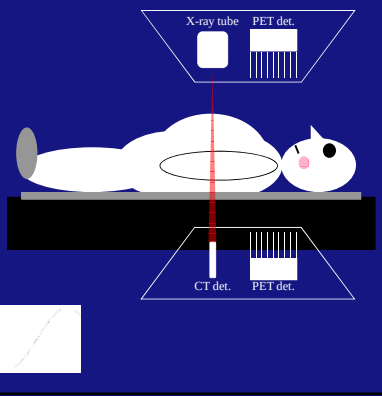


Detector configuration for 4D-CT

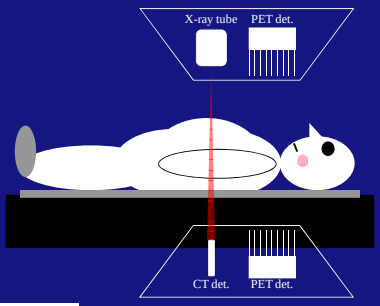


SCALEABLE MULTI-SLICE X-RAY DETECTION

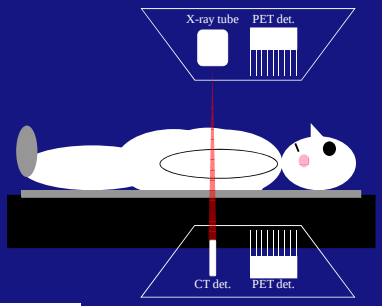
4D-CT Data Acquisition

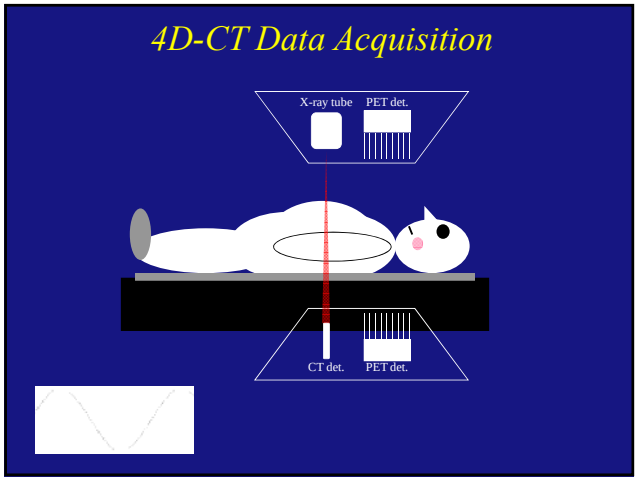


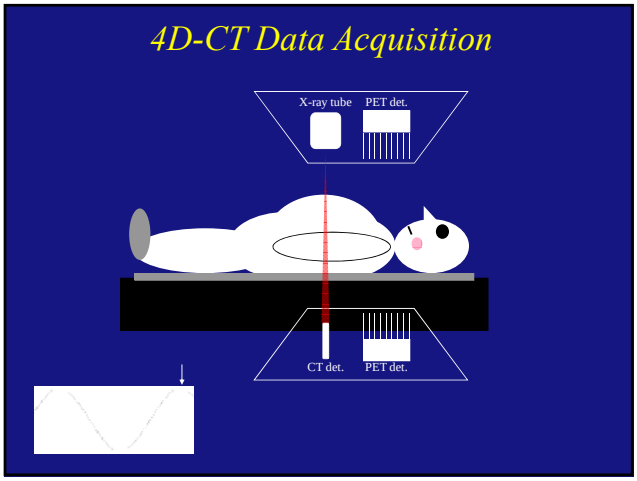
4D-CT Data Acquisition

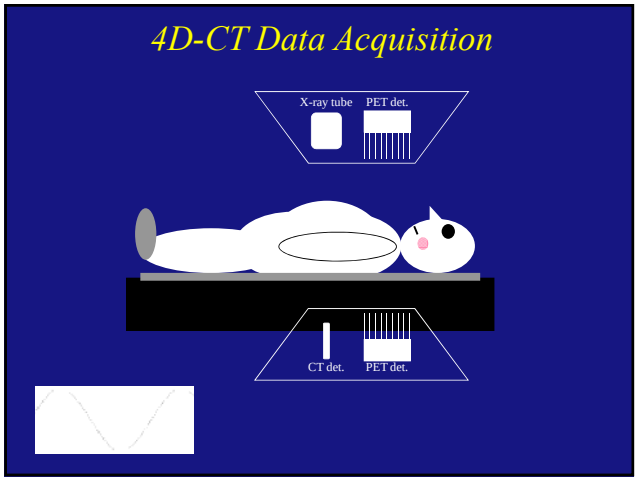


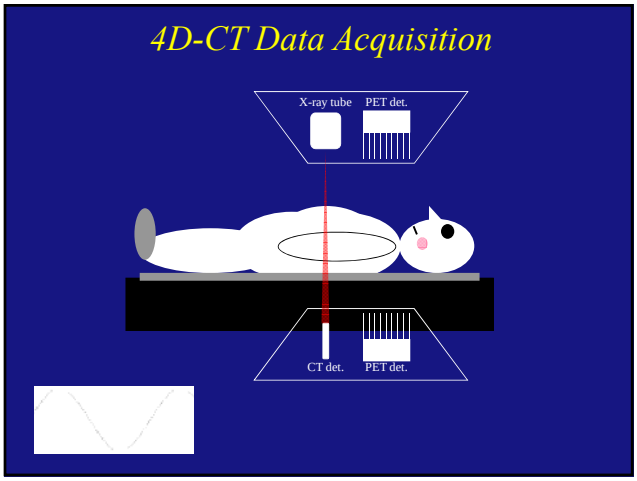
4D-CT Data Acquisition

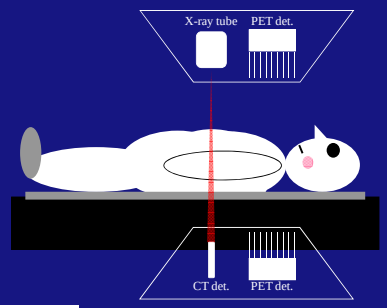


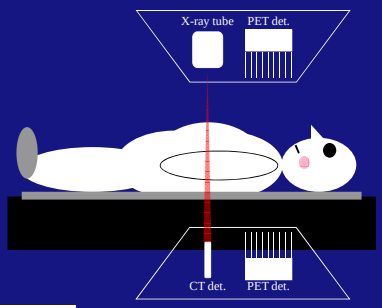

4D-CT Data Acquisition
X-ray tube
PET det.
CT det.
PET det.

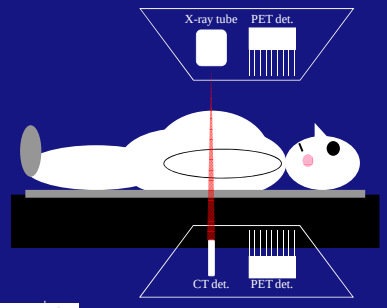

4D-CT Data Acquisition
X-ray tube
PET det.
CT det.
PET det.

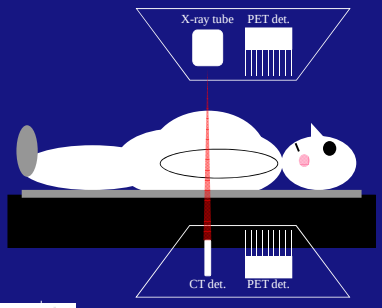

4D-CT Data Acquisition
X-ray tube
PET det.
CT det.
PET det.


4D-CT Data Acquisition
X-ray tube
PET det.
CT det.
PET det.









4D-CT Data Acquisition

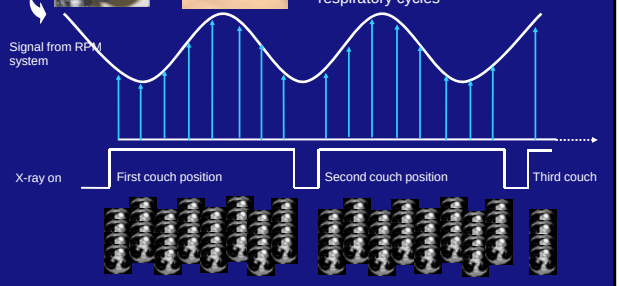
4D-CT Data Acquisition

4D-CT Data Acquisition

4D-CT Data Acquisition

4D-CT

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



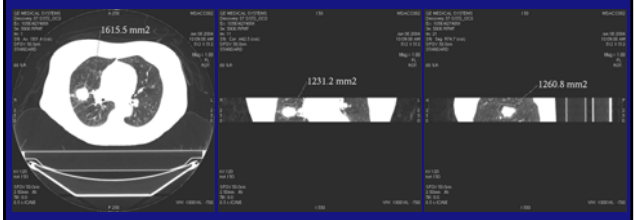
Pan et al, Med Phys, 2004

1st clinical case from MGH

55 sec Cine scan (200 mAs sec per step),
with free breathing of 3.72 sec average breathing cycle

MGH

4D-CT patient study (1)

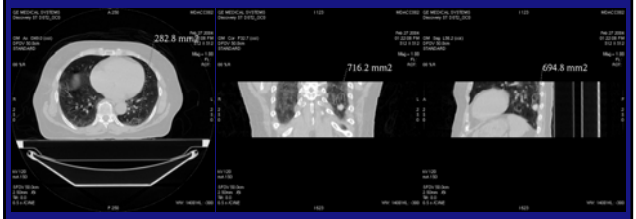


Axial Coronal Sagittal

4D-CT patient study (2)

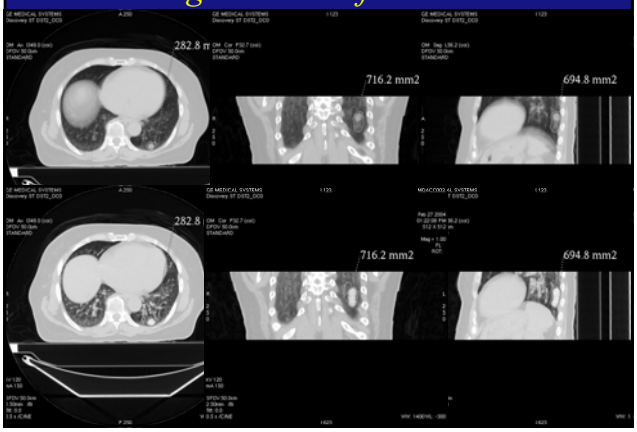
Axial Coronal Sagittal

4D-CT patient study (3)



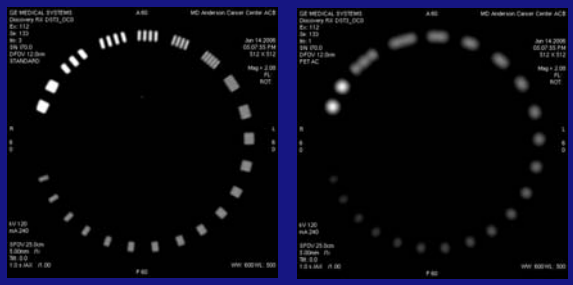
Axial Coronal Sagittal

Average and MIP from 4D-CT



Current PET/CT only matches spatial not <u>temporal</u> resolution between PET and CT

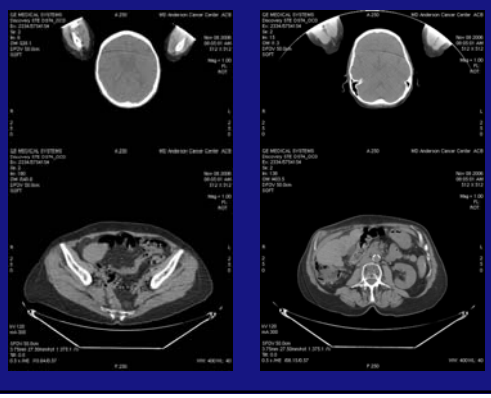
High contrast resolution



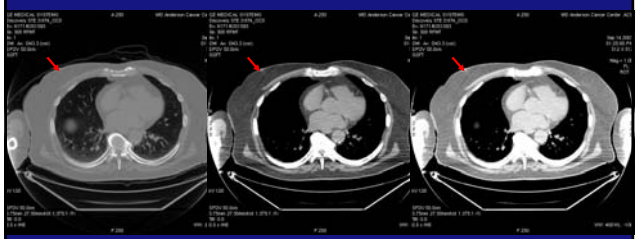
Standard, 7.5 lp/cm, 0.67 mm PETAC, 2.5 lp/cm, 2 mm

Ring Artifacts
in 120 kV not in 140 kV

Ring artifacts from CT

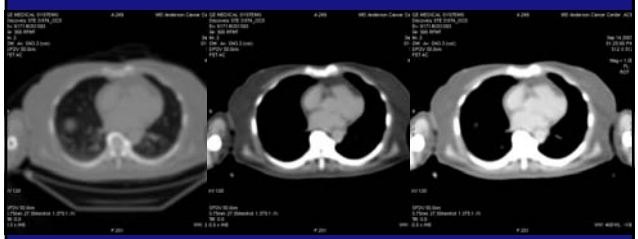


Ring artifacts at different window & levels



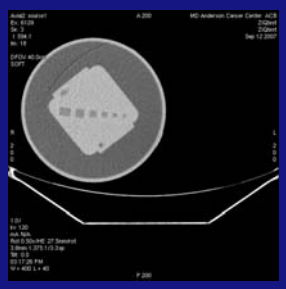
WW=2000, WL=0 | WW=400, WL=0 | WW=400, WL= -100

These are what PET sees

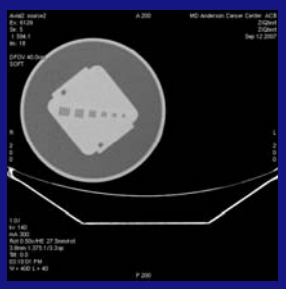


WW=2000, WL=0 | WW=400, WL=0 | WW=400, WL= -100

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

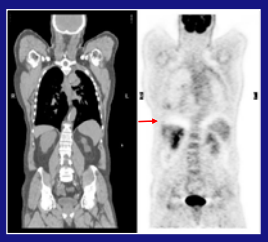
- scan of 15 cm for 3 to 6 mins,
- spatial resolution ~ 5-8 mm
- temporal resolution ~ breathing cycle

CT – 0.5 sec rotation

- scan of 90 cm < 20 sec
- spatial resolution < 0.5 mm
- temporal resolution < 1 sec

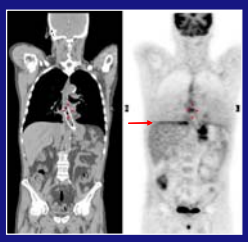
Potential misalignment between PET and CT images

Mis-matched PET-CT data sets



Mismatch 1:

CT diaphgram position lower than PET



Mismatch 2:

CT diaphgram position higher than PET

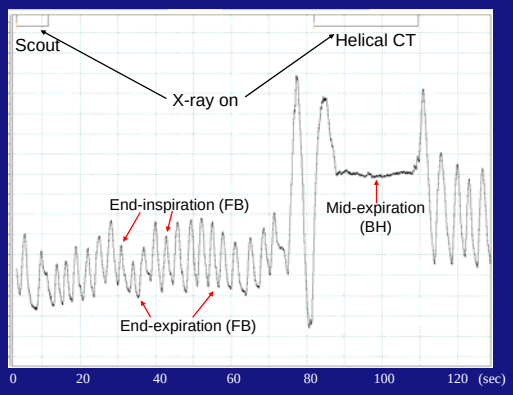
PET/CT protocol

- 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)

30 mins per patient

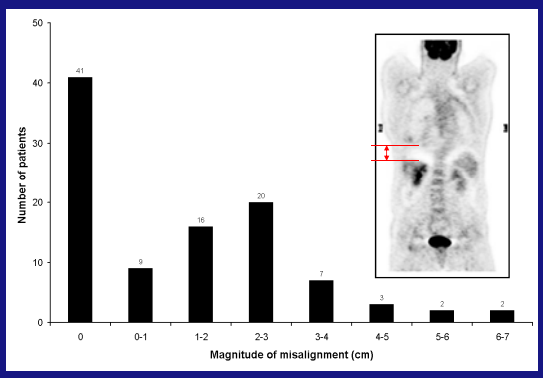
Breath-hold or free-breathing in CT ?

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

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

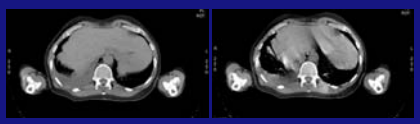
Basic CT scan modes

Axial (Step and shoot)	Axial (step and shoot) $ (low dose cardiac, CACS) $	Cine $ (4DCT) $
one rotation (<= 4 s) one rot.(<= 2 s for 64-slice)	2/3 rotation	multiple rotations
Helical	$ Helical $ $ (cardiac) $	$ Helical $ $ (4DCT) $
pitch 0.5 to 1.5	pitch 0.2 to 0.3	pitch < 0.1

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

Slow scan CT artifacts

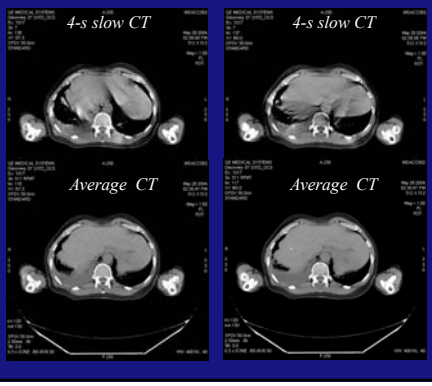
0.5 sec rotation 4 sec rotation



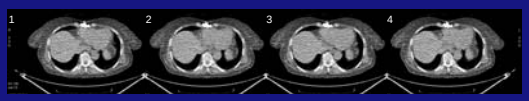
Average CT (4 sec) Slow CT (4 sec)

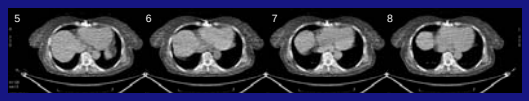
Average CT is better than slow CT

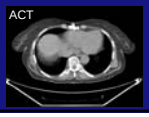
(2 adjacent CT slices of 2.5 mm apart)



High radiation dose with cine CT ?

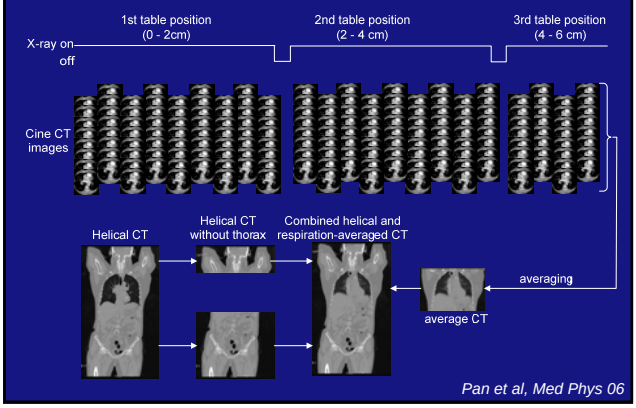






60 mAs & 1.2 mSv

Cine CT averaging



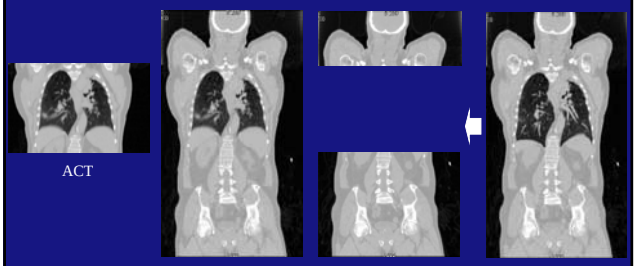
Pan et al, Med Phys 06

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

30 mins per patient

Creating Average CT



ACT

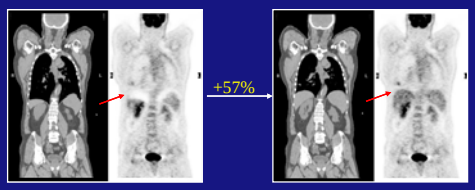
Helical CT w ACT | Helical CT w/o thorax | Helical CT

Clinical Data

Clinical Studies

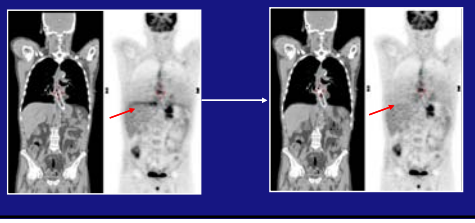
Mismatch 1:

CT diaphgram position lower than PET



Mismatch 2:

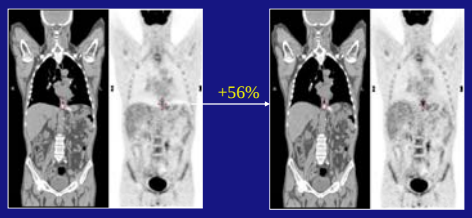
CT diaphgram position higher than PET



Clinical Studies

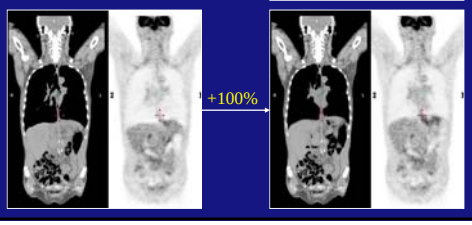
Mismatch 3:

CT diaphgram position lower than PET



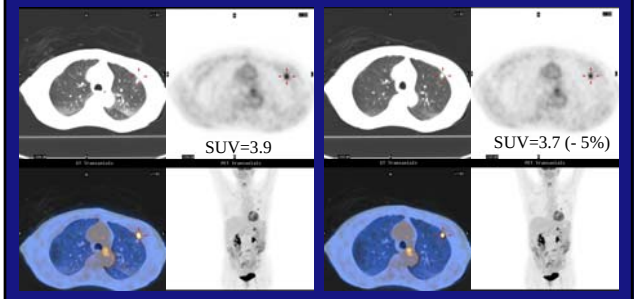
Mismatch 4:

CT diaphgram position lower than PET

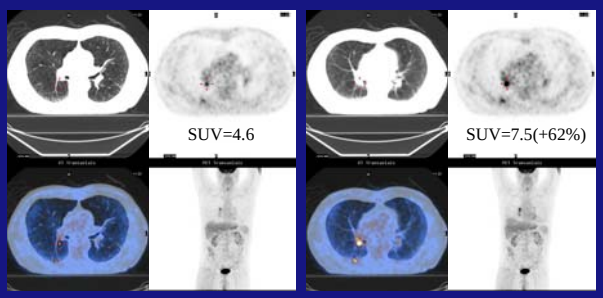


Patient study #1

Patient study #2

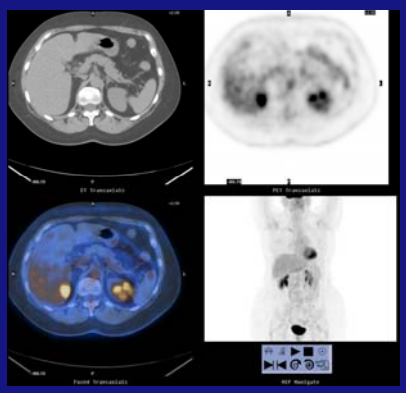


Patient study #3



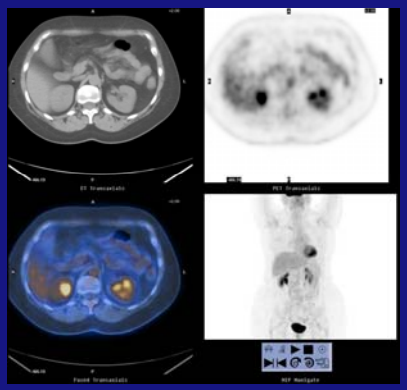
FDG uptake in the liver?

HCT

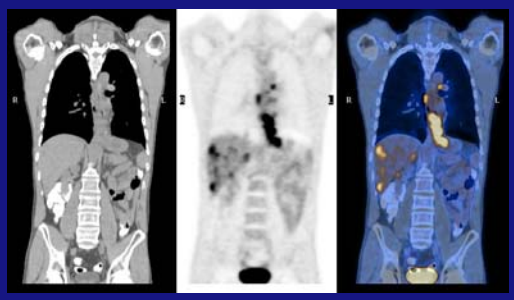


FDG uptake in the kidney

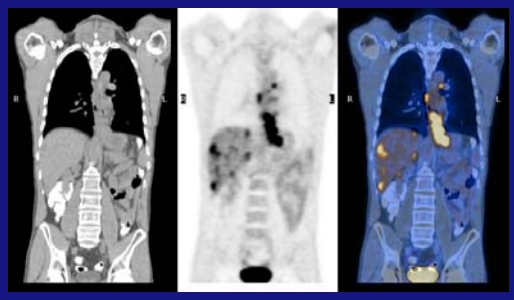
ACT



Lung lesion or liver lesion?

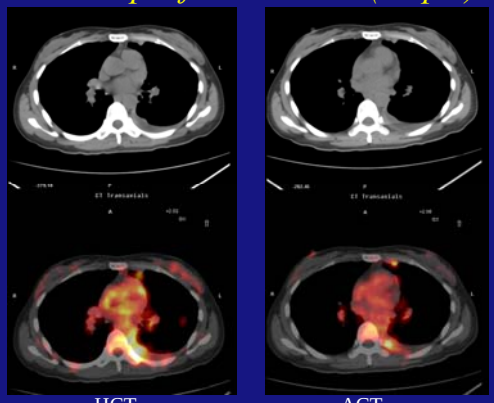


Lung lesion or liver lesion?



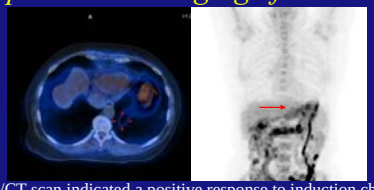
Average CT

Example from CGMH (Taipei)

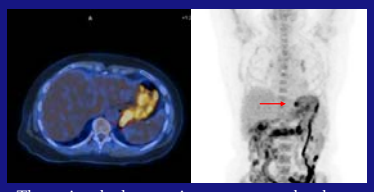


HCT ACT

Improve the restaging after chemo



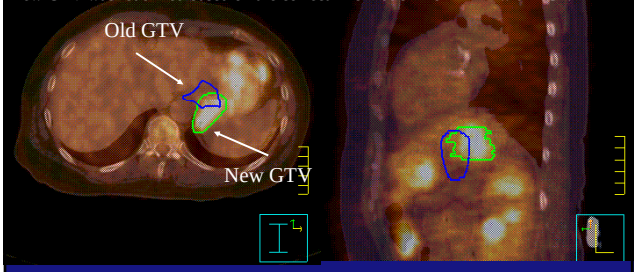
PET/CT scan indicated a positive response to induction chemo with HCT.



The patient had a negative response to the chemo with ACT.

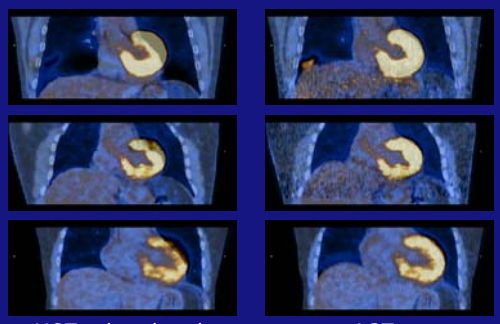
Impact on treatment planning

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.



Provided by Helen Liu

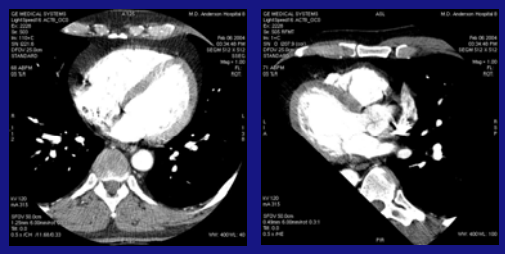
Average CT in cardiac PET



HCT- misregistration ACT

Pan et al, Med. Phys. 2006

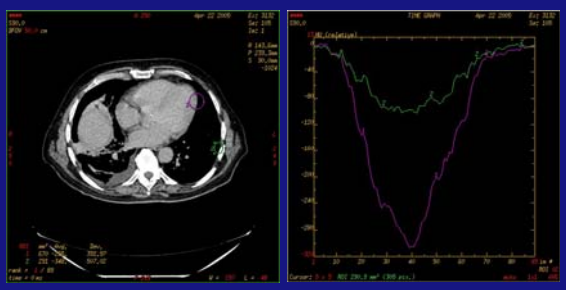
Heart motion in breath-hold



250 msec temporal resolution

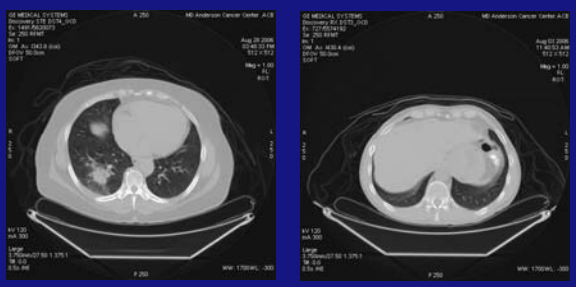
The heart does not seem to move in space during the breath-hold

Cardiac and respiratory motion



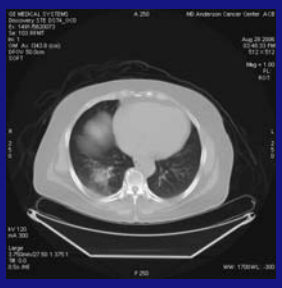
500 msec temporal resolution and 100 msec interval between reconstructions

Table shifted between HCT and ACT



HCT (correct table) HCT (incorrect table)

Table shift between HCT and ACT



ACT (correct table)

ACT (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