

# Imaging in Radiotherapy

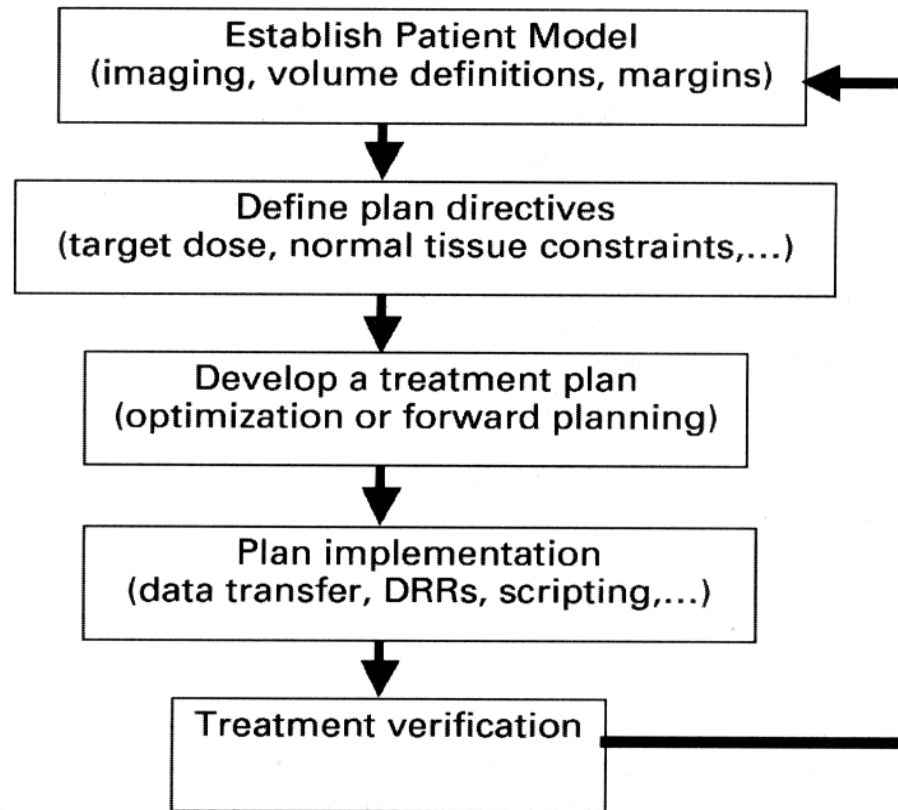
Present and Potential Uses

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# A Radiotherapy Flowchart

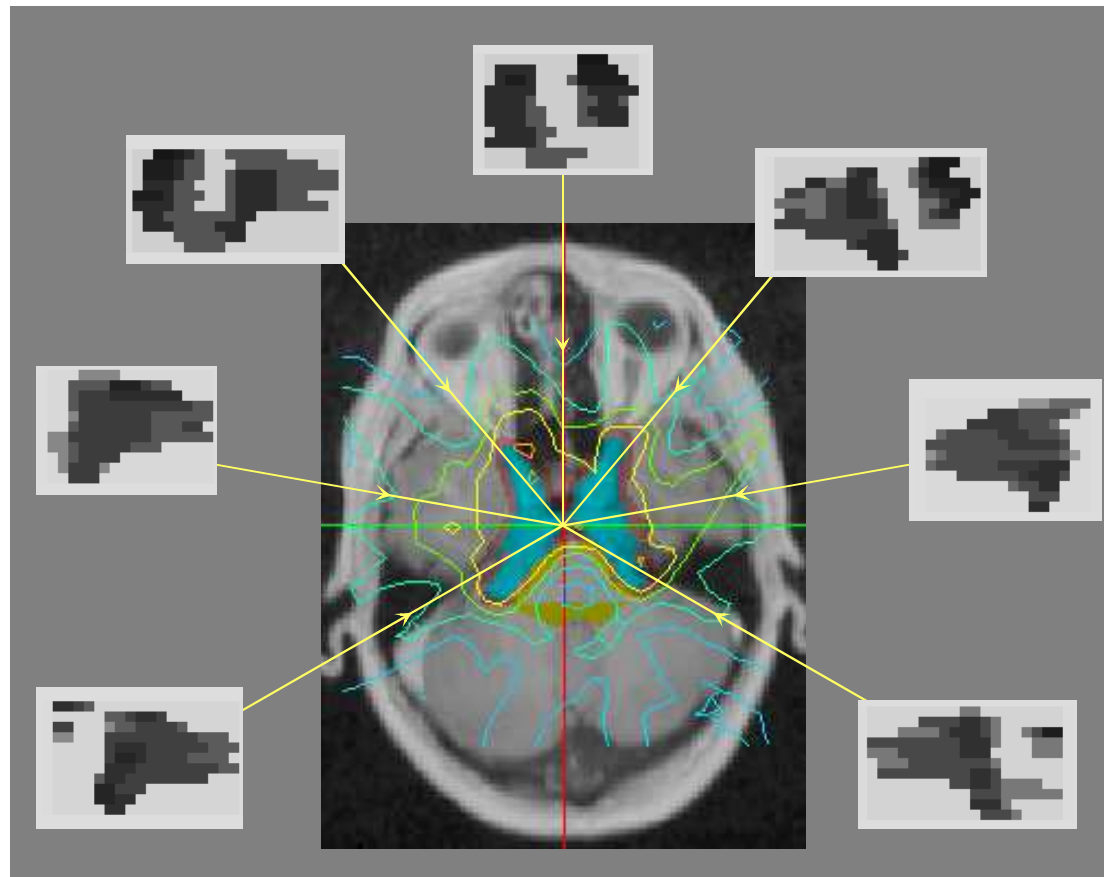


**Figure 1.** Overview of the radiotherapy process.

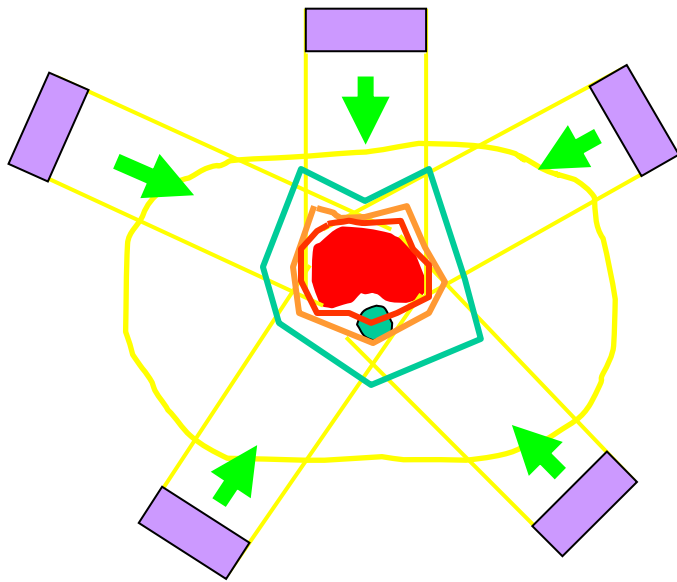
# RT Developments

	Conformal (early 90s)	IMRT (late 90s)	IGRT (now)
Imaging data	Single CT	Single CT	<b>Multiple X-ray</b>
	MR, FDG	MR, FDG	MR, FDG
	Fusion	Fusion	Fusion
Planning	Forward	<b>Inverse</b>	Inverse
Treatment	MLC	MLC + sequencing	<b>IMRT + on-line X- rays</b>

IMRT = dose sculpting

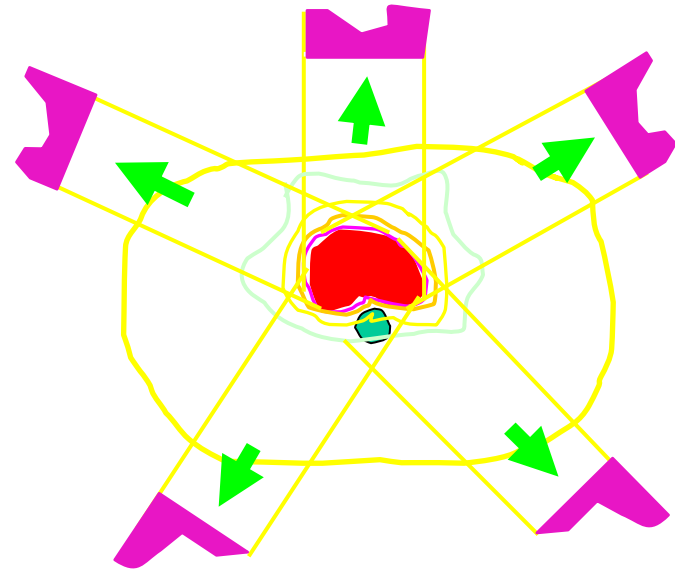


# Thinking backwards



## Forward planning

"Lets see what dose we get with this combination of beams ..."



## Inverse planning

"This is the dose I want, what beam modulation do I need?"

# The "Quadratic Differences" objective function

Strive to minimise  
this value,  $L$

$$L = \sum_{i=1}^N \left( D_i(\mathbf{x}) - D_i^p \right)^2$$

Sum the  
differences for all  
voxels ( $i$  to  $N$ )

Current calculated  
dose in voxel  $i$

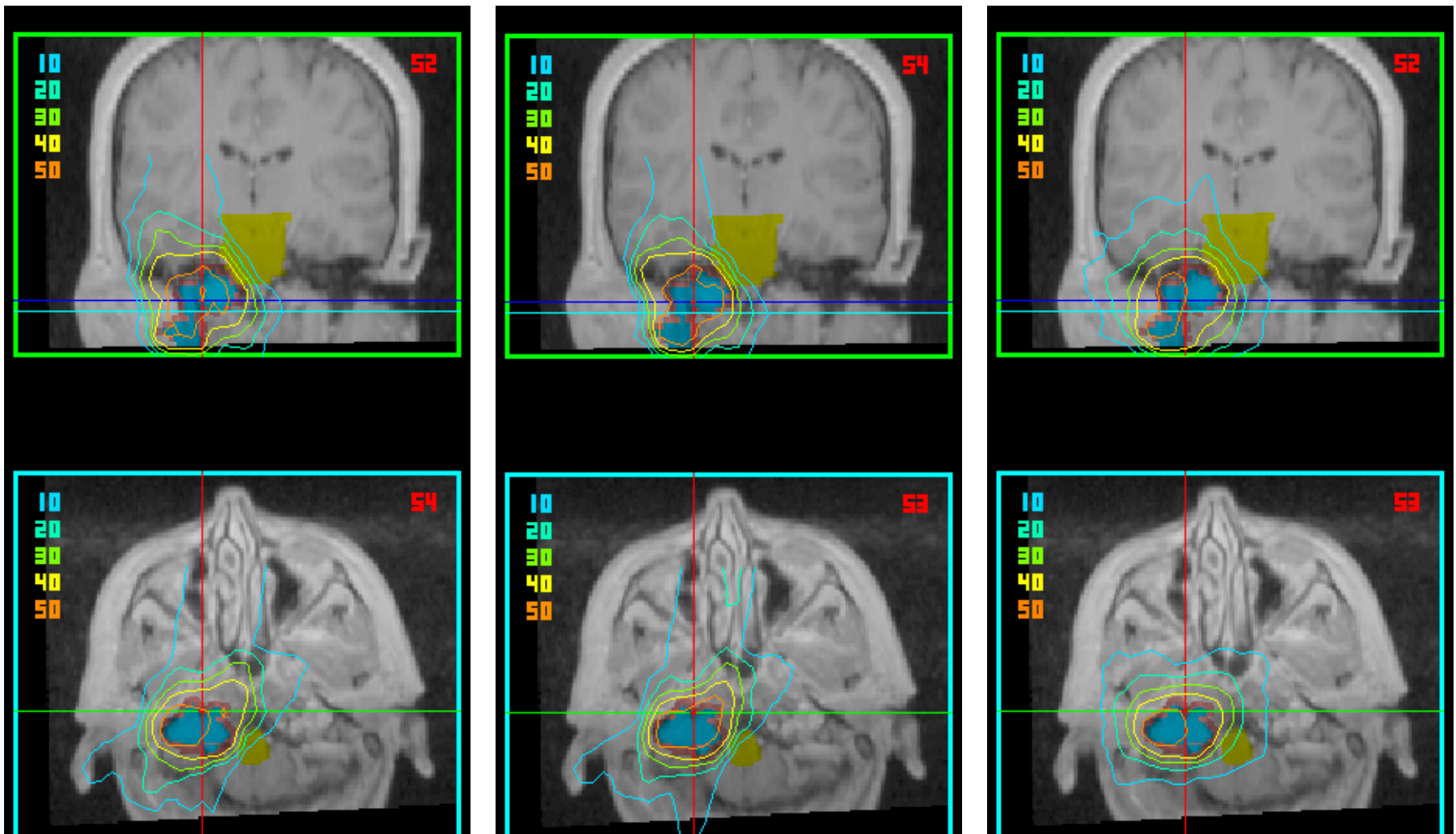
Desired dose in  
voxel  $i$

# Isodose Comparison

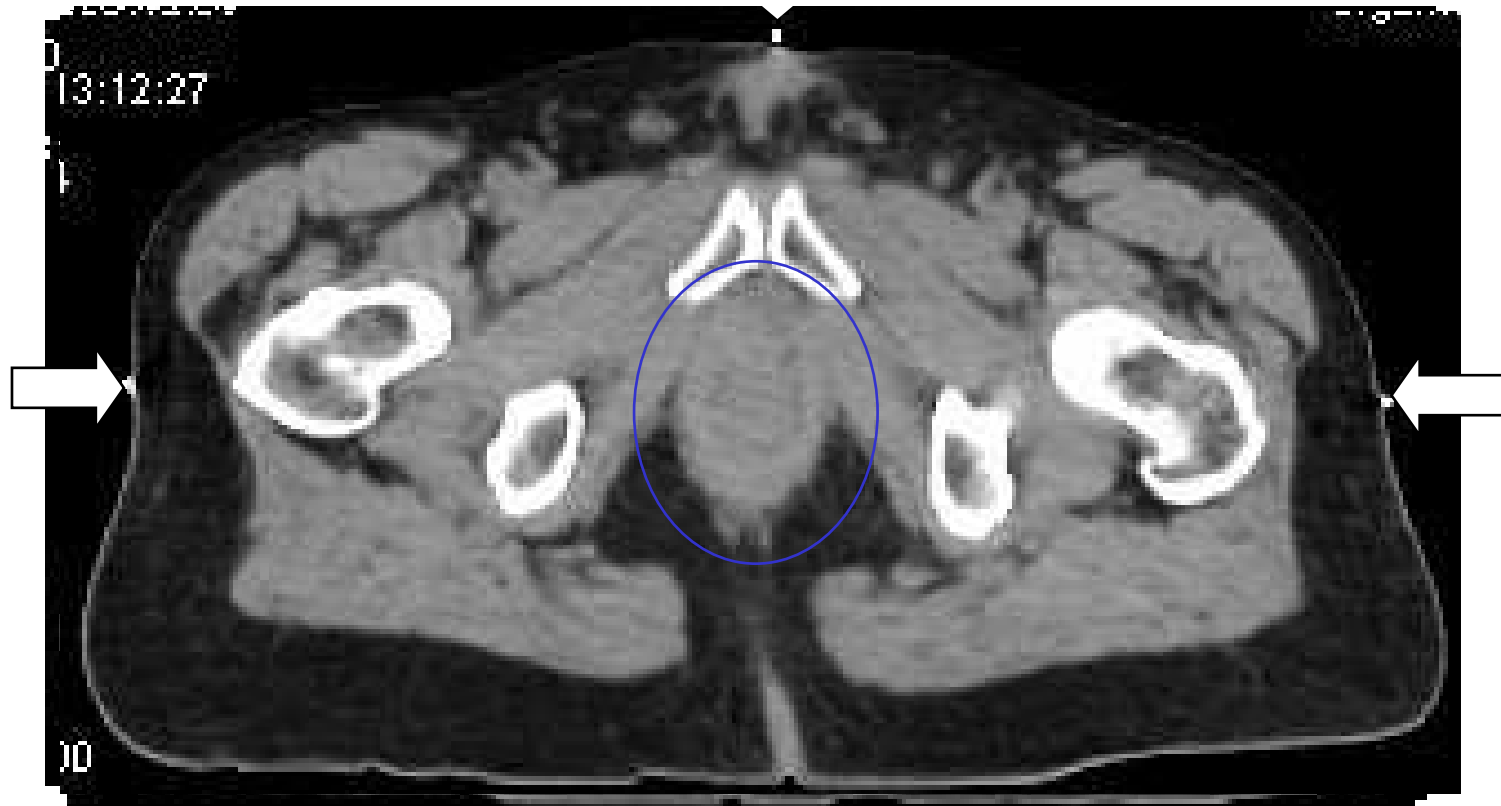
Fixed fields

IMRT

Conformal Arcs



# The Travels of a Prostate



# The PTV and Localisation Techniques

- Stereotactic frames
- Rectal Balloon
- Ultrasound
- Radio-Opaque Markers
- Orthogonal imaging using kV X-rays
- Daily CT (cone beam or tomographic)
- Gated Techniques - Breath hold

# IMRT → IGRT → ART

- MLCs + optimisation = IMRT - the ability to 'sculpt' dose delivery.
- Next step: target the tumour via on-line imaging → image guided radiation therapy (IGRT).
- Extensive work is being conducted by linac vendors into the use of kV or MV x-rays for imaging.
- From IGRT, the next step is ART, Adaptive X-Ray Therapy. Use the information gained at treatment time to adjust the treatment delivery on a day-to-day basis.

# IGRT - the majors

- Elekta Synergy™ has a linac which includes a retractable kV source mounted at 90° to the treatment head with an a-Si flat panel. This is addition to the a-Si flat panel positioned in line with the megavoltage beam.
- Siemens have placed a multi-slice CT in the same room as their linear accelerator. Tumour position is determined via the 3D CT scan, and the delivery can be adjusted if necessary.
- The Varian Trilogy™ accelerators integrates a kV X-ray source with a flat panel detector. This can be used for planar and cone beam CT.

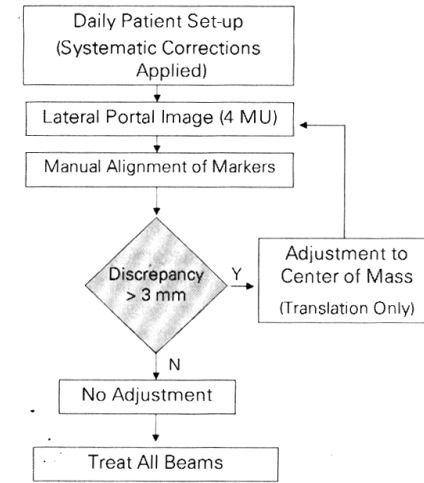


# IGRT - the minors

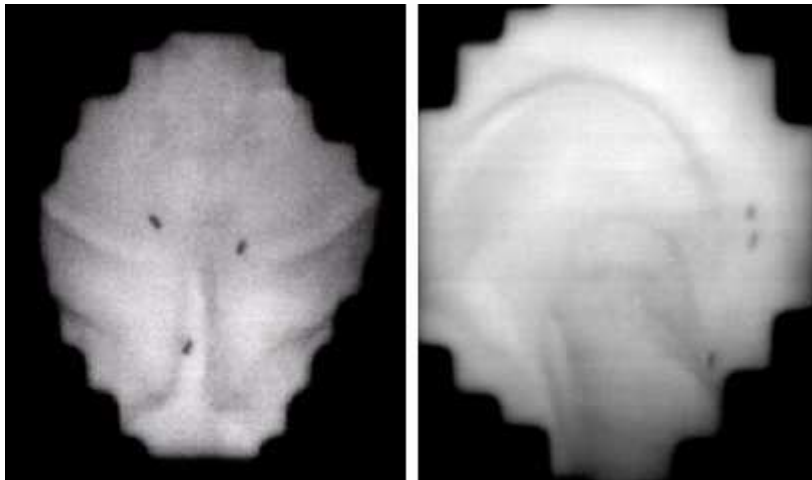
- CyberKnife™ has a linac attached to a robotic arm. Combined use of kV x-rays sources and a-Si image detectors. Predominantly used for radiosurgery without the need for a rigid and invasive localisation frame. ~50 worldwide
- BrainLAB's Novalis™ system uses kV x-rays and a-Si detectors for bony landmark localisation, and infra-red detectors for external localisation. This is a specialised stereotactic machine with a MMLC attached to a linac. ~70 worldwide
- Tomotherapy™ broke the paradigm by putting a linac waveguide in a CT ring. MVCT images taken prior to treatment make accurate tumour localisation possible. Exit dose is also used to map delivered doses. ~20 worldwide



# IGRT - Low Tech



**Figure 6.** Daily on-line imaging and correction procedure for marker-based image-guided radiation therapy of the prostate. In this procedure, a single lateral portal image is taken to permit re-positioning in the anterior-posterior (AP) and superior-inferior (SI) directions. Intervention is required approximately 19% of the time. [Courtesy of T. Haycocks M.R.T.(T), Princess Margaret Hospital, Toronto, Canada]



**COUCH MOVES**

To move the target to the isocenter, position couch as follows (in mm):

left	2.4	in	1.2	up	3.4
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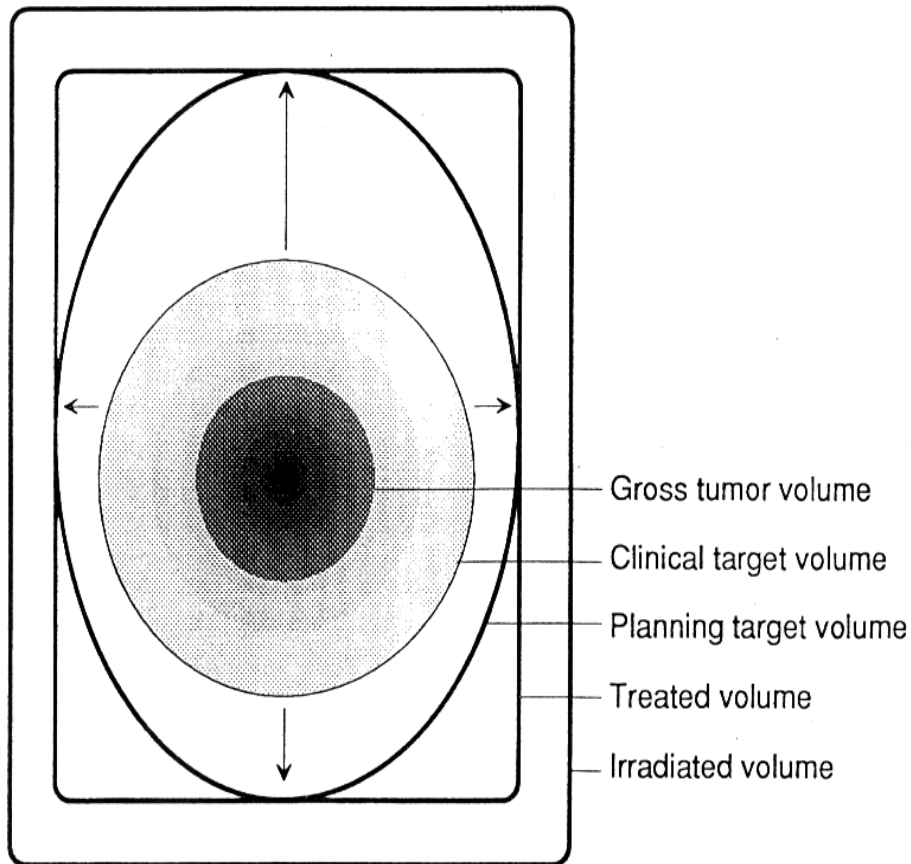
Comparison of distances in CT system with those of treatment machine system (in mm)

	1-2	2-3	3-1
Difference (mm):	0.1	0.4	0.3

Transformation from the XYZct to the XYZf system that places the target at Isocenter

theta, ccw about Xct:	-2.9	phi, ccw about Zct:	0.9	psi, ccw about Yct:	3.6
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# RT Contouring



## GTV

*"The **Gross Tumour Volume** is the visible/demonstrable extent and location of malignant growth."* Obtained from imaging data and physical examination

## CTV

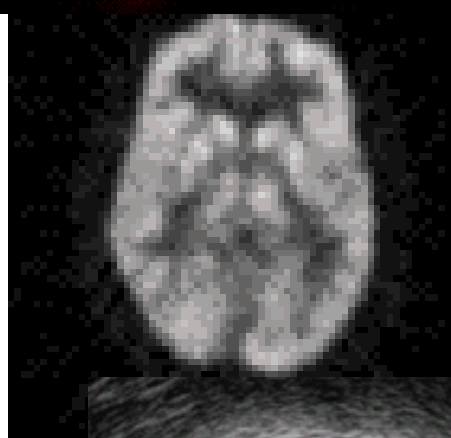
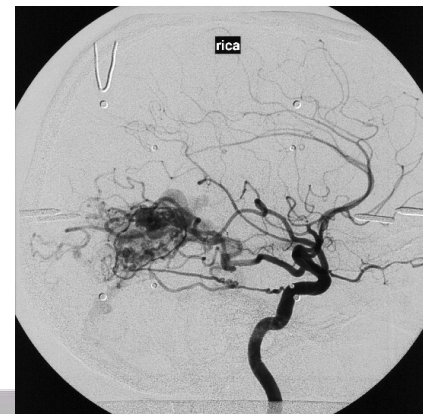
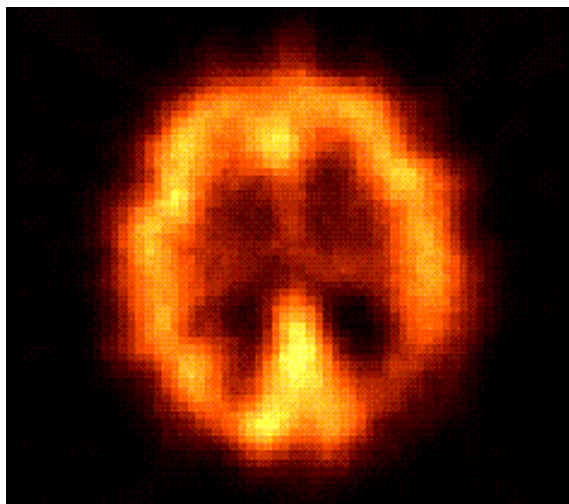
*"The **Clinical Target Volume** is the tissue volume that contains subclinical microscopic disease which has to be eliminated. It must be treated adequately to achieve the aim of therapy, cure or palliation."* Usually stated as a fixed or variable margin around the GTV

## PTV

*"The **Planning Target Volume** is defined to select the appropriate beam arrangements, taking into consideration all possible geometrical variations, to ensure that the prescribed dose is absorbed in the CTV."*

Usually defined as the CTV + treatment margins. Therefore, it is dependant on the physical set-up accuracy.

# Data Sets



MONICS  
fe™ RT2

MO\_RT2

er Beam Dose

New

Delete

Table

7.2

centers

Coronal 168/320 S 191.2 (mm)

R L

I

1-CT-Axial

Axial 17/53 A 108.0 (mm)

R L

P

1-CT-Axial

Coronal 168/320 S 119.5 (mm)

R L

I

2-MR-Axial

Axial 17/53 A 16.6 (mm)

R L

P

2-MR-Axial

**Table 3. Multi-Modality Imaging. Bracketed (x) Denote “Under Development”**

Feature	Simulator	CT	MRI	MRS	SPECT PET	Ultra- sound	Portal Imaging
Open Gantry	x	(x)			(x)		x
Projection	x	x	(x)				x
Tomography		x	x		x	x	
Beam's Eye View	x	x	(x)				x
Fluoroscopy	x					x	(x)
Surface Contours	x	x	x			x	
Tissue Electron Densities		x					
Vasculature	x	x	x			x	
Gross Target Volume	x	x	x		x	x	(x)
Organs at Risk	x	x	x		x	x	(x)
Clinical Target Volume			x	x			
Planning Target Volume	x	x					(x)
Biological Target Volume			x	x	x		
Verification		x				x	x
3-D Dosimetry		x	x	(x)			

# Multiple Image Modalities

**RADIONICS**  
ImageFusion

**Results**  
Patient: WATANABE, Saaya 0

Average Landmark distances (mm)

Total:	2.8
In-plane:	2.7
Out-plane:	0.7
L-R:	0.3
A-P:	-0.6
S-I:	-0.7

Messages  
Restored fuse done using intensity match.

**Scan 1: Split-slice**  
Axial A 16.0 (z)  
R L I  
P

**Scan 2: Split-slice**  
Coronal S 177.0 (y)  
R L  
I

**Scan 1**  
Axial A 8.0 (z)  
R L  
P

**Scan 2**  
Axial A 29.0 (z)  
R L  
P

# From GTV to BTV

- Seen via imaging from
  - planar X-rays of the simulator
  - rotational CT imaging
  - proton density of MR
  - metabolic activity of PET, fMR
- But what is the tumour or target?
- The addition of metabolic information to the known anatomy = Biological Target Volume (BTV)

# Uses of FDG-PET

- Over 1000 scans per year, with some centres reporting closer to 2000.
- At least over 90% of the cases are oncology related.
- Some US numbers of FDG-PET scans.
  - 1998 70,000,
  - for 1999 106,000 and
  - approximately 350,000 for the year 2002.
  - ~2,000,000 by 2007!!!



# Potential Role for FDG-PET

- Staging

- Radiation Therapy Planning

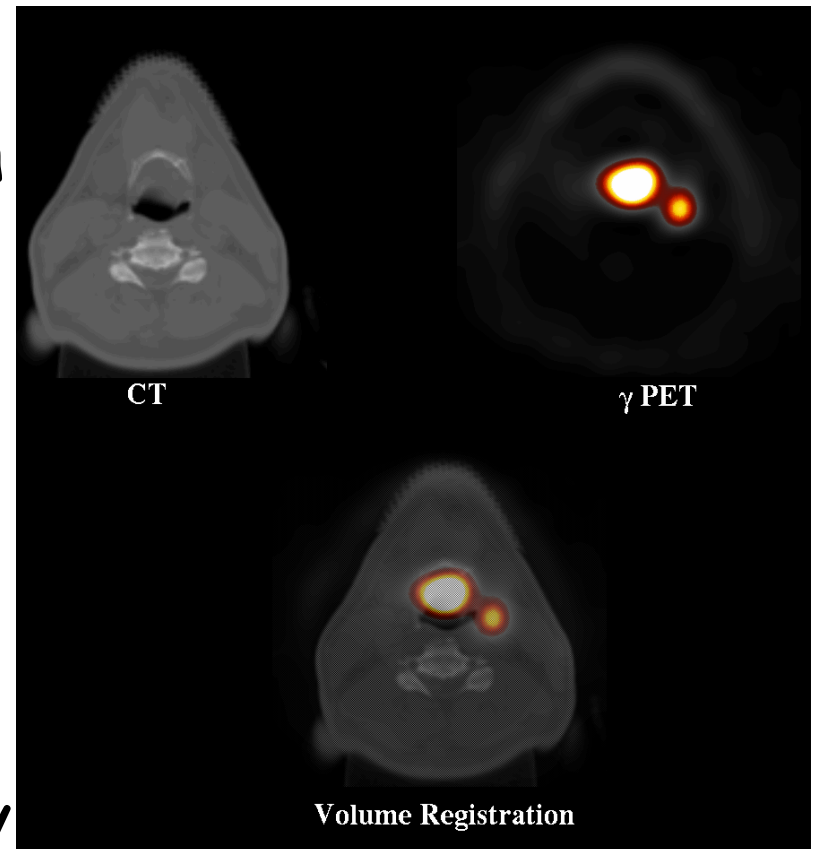
- Post-Treatment Response

# Clinical indications - NSCLC

- Initial use of PET is for staging and the recognition of benign over malignant disease, the future work will be a change in the actual volume to be treated
- Distant metastases identified in 10-30% of stages I - III NSCLC
- Upstaging in 10-20% of cases due to nodal involvement
- 102 patients, the use of PET (J of NM, 45(1))
  - 11 distant metastases detected
  - Lowered staging in 20
  - Upstage in 42

# FDG-PET : Advantages

- High contrast images
- Better distinction between disease and other conditions that are similar in density e.g., edema, fibrosis, minor inflammation
- Improved detection of pathologic lymph nodes based on metabolic activity rather than size



# FDG-PET for Lung Cancer Staging

*Where is it effective?*

- Extent of primary tumour
- Extent of disease throughout the body
- Detection of pathological mediastinal lymph nodes
- Estimated 37% change in management

# FDG-PET for Staging

<b>Cancer</b>	<b>Pt Studies</b>	<b>No. of Papers</b>	<b>Accuracy PET</b>	<b>Accuracy CT</b>
<b>Lung</b>	<b>1867</b>	<b>53</b>	<b>82</b>	<b>68</b>
<b>Breast</b>	<b>1473</b>	<b>20</b>	<b>90</b>	<b>na</b>
<b>Lymphoma</b>	<b>1433</b>	<b>34</b>	<b>88</b>	<b>64</b>
<b>Gastro-eso</b>	<b>654</b>	<b>11</b>	<b>83</b>	<b>68</b>
<b>H&amp;N</b>	<b>659</b>	<b>15</b>	<b>88</b>	<b>67</b>
<b>Gynae</b>	<b>443</b>	<b>5</b>	<b>54;96*</b>	<b>48;76*</b>

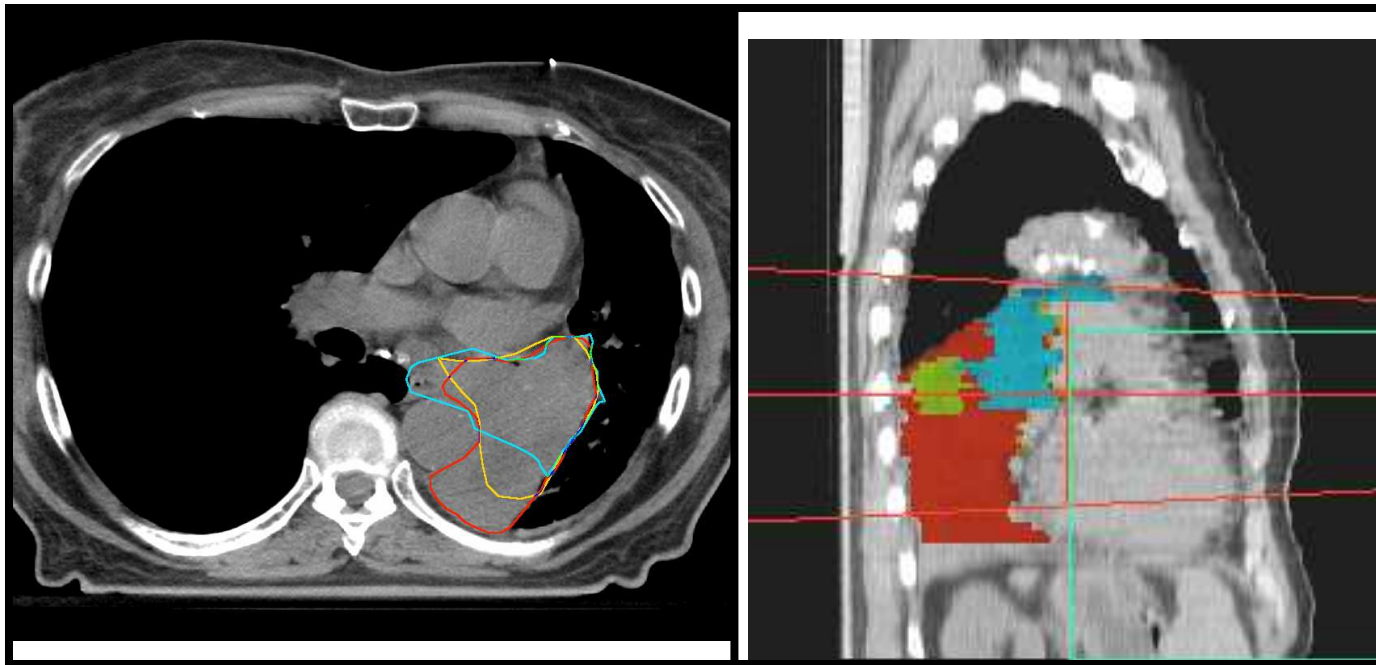
- **Sensitivity;Specificity values : Accuracy not calculated**
- **Data from Table 20 J Nuc Med 42 Supp 5, 2001**

# For NSCLC nodal staging, size is not enough!

- Gupta NC et al. (Chest 2000) measured an overall accuracy of 92% with FDG-PET in identifying involved lymph nodes < 1 cm in size as seen on CT.
- Of 53 small (< 1 cm) lymph nodes sampled from 54 patients with NSCLC:
  - 17 were positive by histology
  - 15 out of 17 were positive on PET
  - 0 out of 17 were positive by CT size criteria

# For 3DCRT of NSCLC, defining the GTV can be difficult with CT alone

3 Physicians; 3 different volumes; 3 different plans



Why?

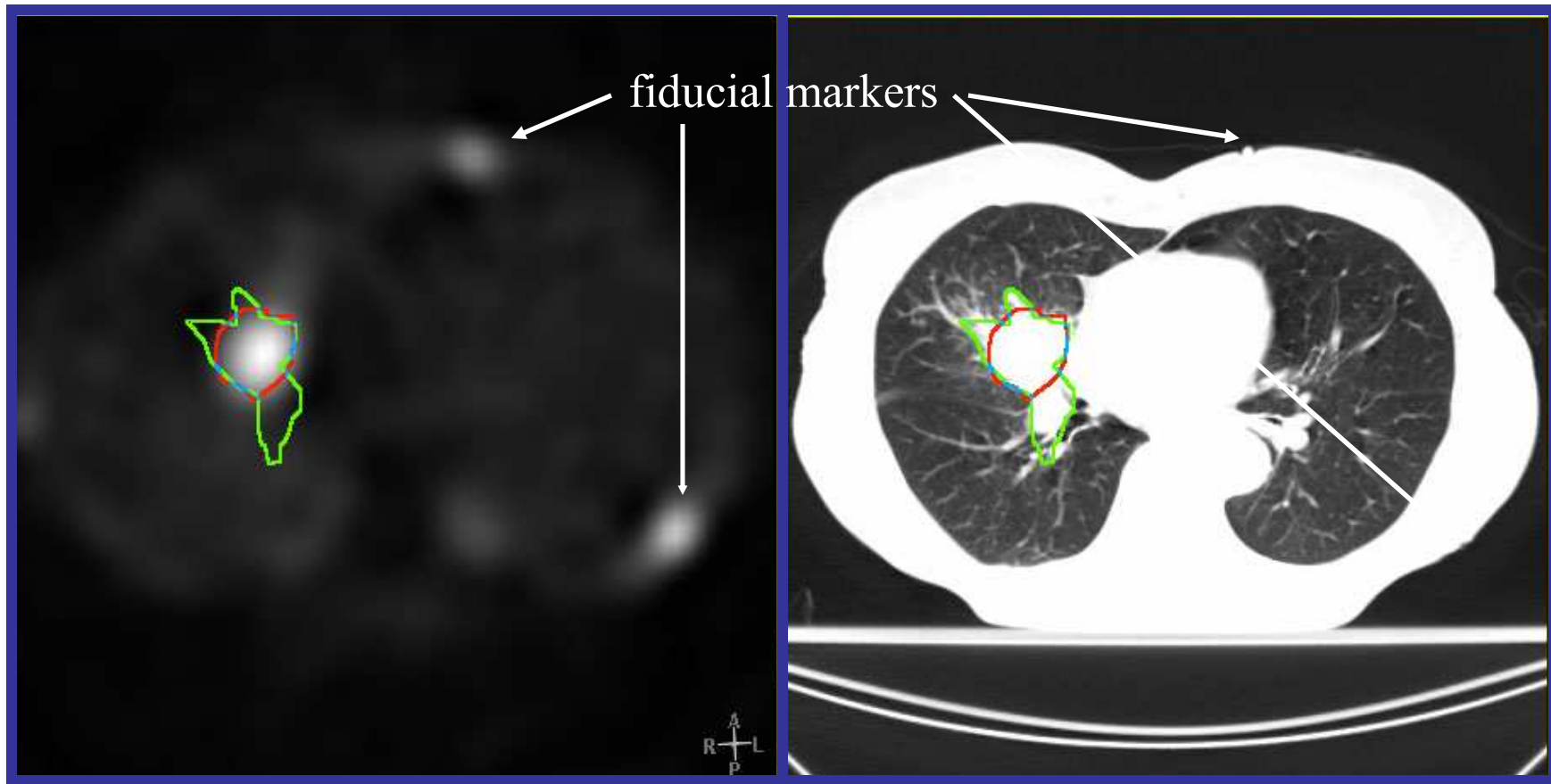
With anatomic imaging, it is difficult to distinguish tumour boundaries from other processes: pneumonitis, normal tissue displacement or lymph node involvement

# Impact of FDG-PET

Year	No. of Patients	Change in RTP
2000	73	45 (61%)
2001	12	5 (41%)
2002	11	9 (82%)
2003	24	14 (58%)

"a significant alteration in tumour volume coverage in ~30-60% of patients with NSCLC whose treatment was planned using  $^{18}\text{F}$ -FDG images"

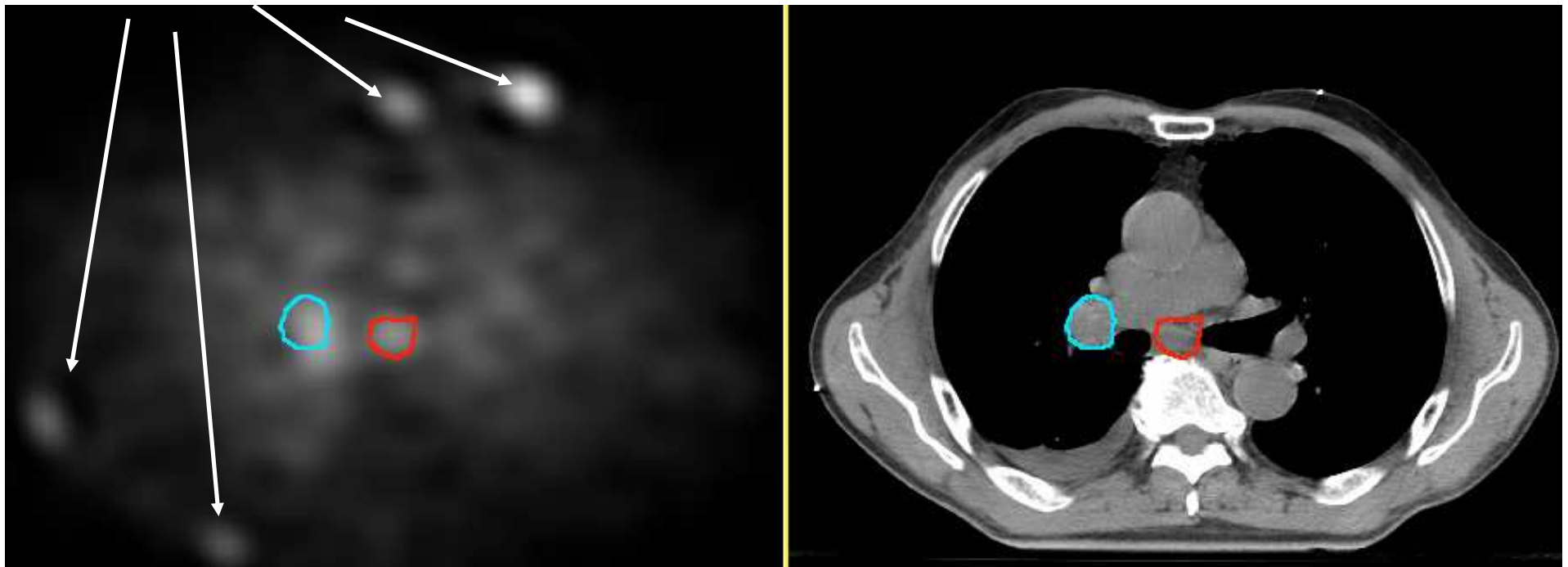
# Case 1: *FDG-PET* decreased the target volume



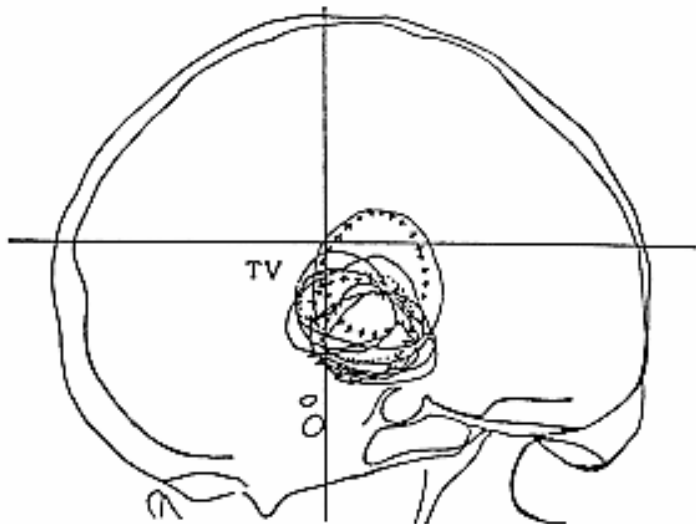
Red Outline: CT and FDG    Green Outline: CT only

# Case 2: *FDG-PET increased the target volume*

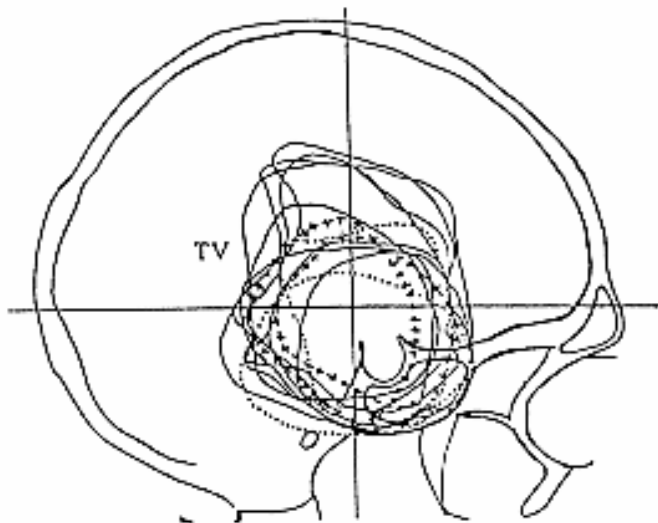
Markers



Primary tumour (blue)  
Involved node found on FDG (red)

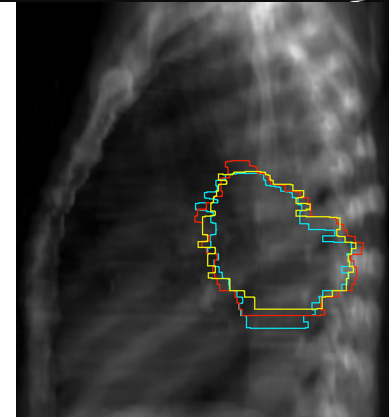
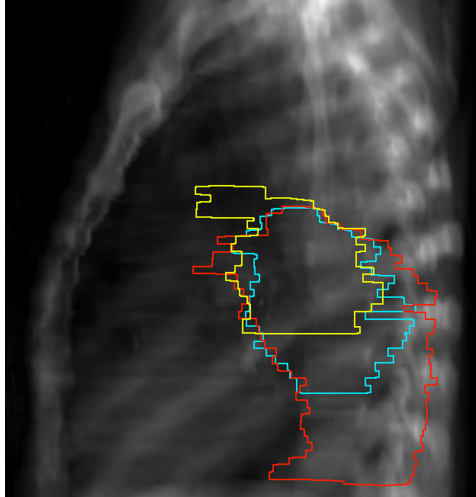
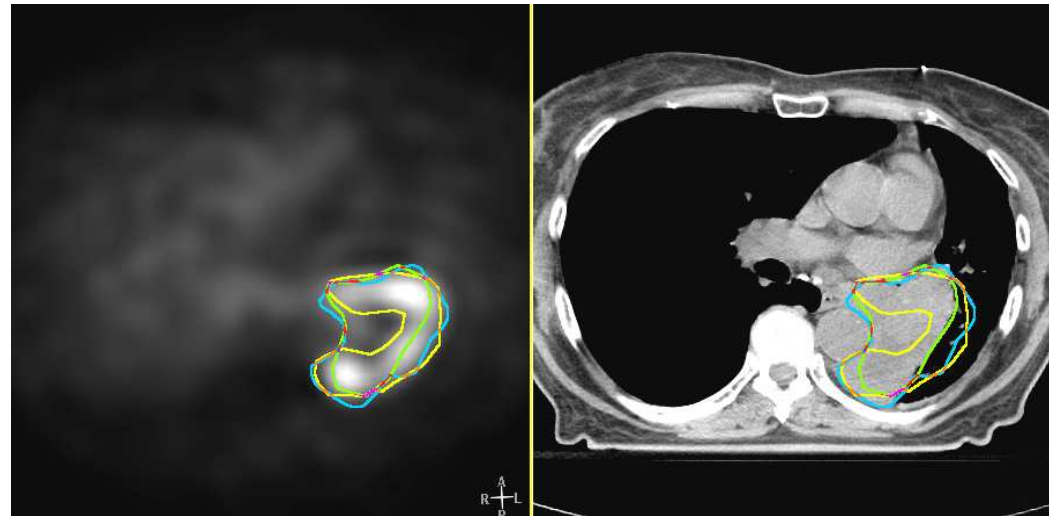
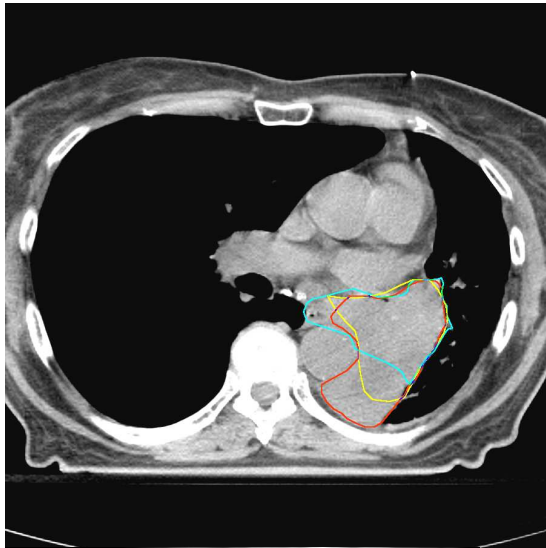


What is the effect of uncertainty in geometry?



GTV outlined by  
8 radoncs (— )  
2 radiodiagnosticians (....)  
2 neurosurgeons (-----)

# Inter-observer variability: Case example



CT variation

CT/FDG variation

Volume range: 91 - 229 cm<sup>3</sup> (ratio 2.52)

Volume range: 117 - 155 cm<sup>3</sup> (ratio 1.32)

# Results: Inter-Observer Variation

Observer variation was quantified as the ratio of largest to smallest  $GTV_{total}$  among three observers.

- In 23 of 30 cases, the addition of FDG decreased variation
- In 7 of 30 cases, the addition of FDG increased variation

mean ratio with CT only	2.31	range [1.06 - 7.66]
mean ratio with CT and FDG	1.56	range [1.09 - 2.77]

# Summary of FDG-PET for RT Planning

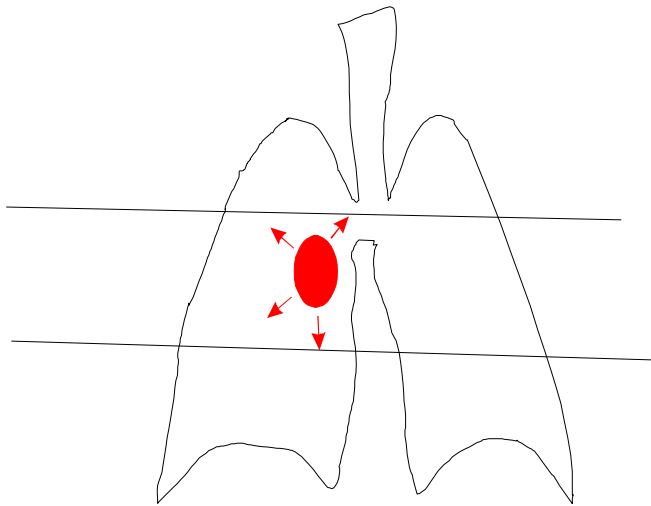
- FDG-PET has great potential for applications in radiation therapy, clearly in lung and possibly in head and neck cancer
- For NSCLC, it can
  - change patient management (staging)
  - reduce observer variability  $\Rightarrow$  consistent GTV
  - significantly change the GTV

# Respiratory Gating

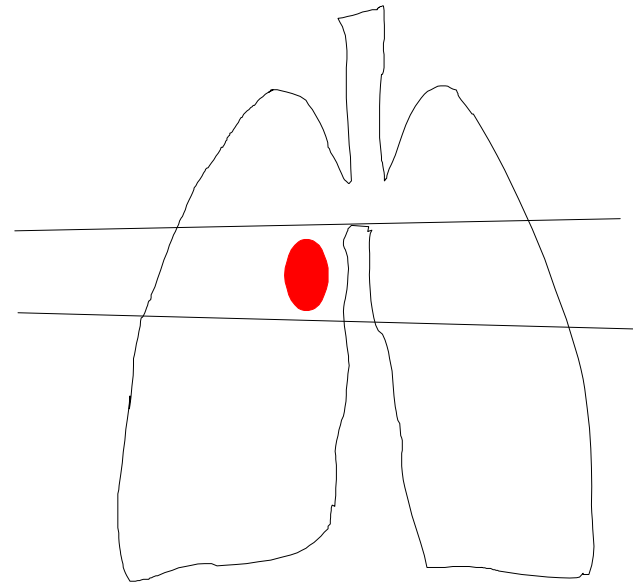
- For lung, liver etc where respiratory motion is large, imaging can be used to help control the effects of breathing.
- Methods:
  - Gate the patient
    - Direct Inspiration Breath Hold
    - Active Breathing Control
  - Gate the machine
    - Optical markers
    - Spirometer
    - Thermistor, strain gauge

# DIBH Concept

- Increase volume of lung *outside* treatment field
- Reduce motion during treatment

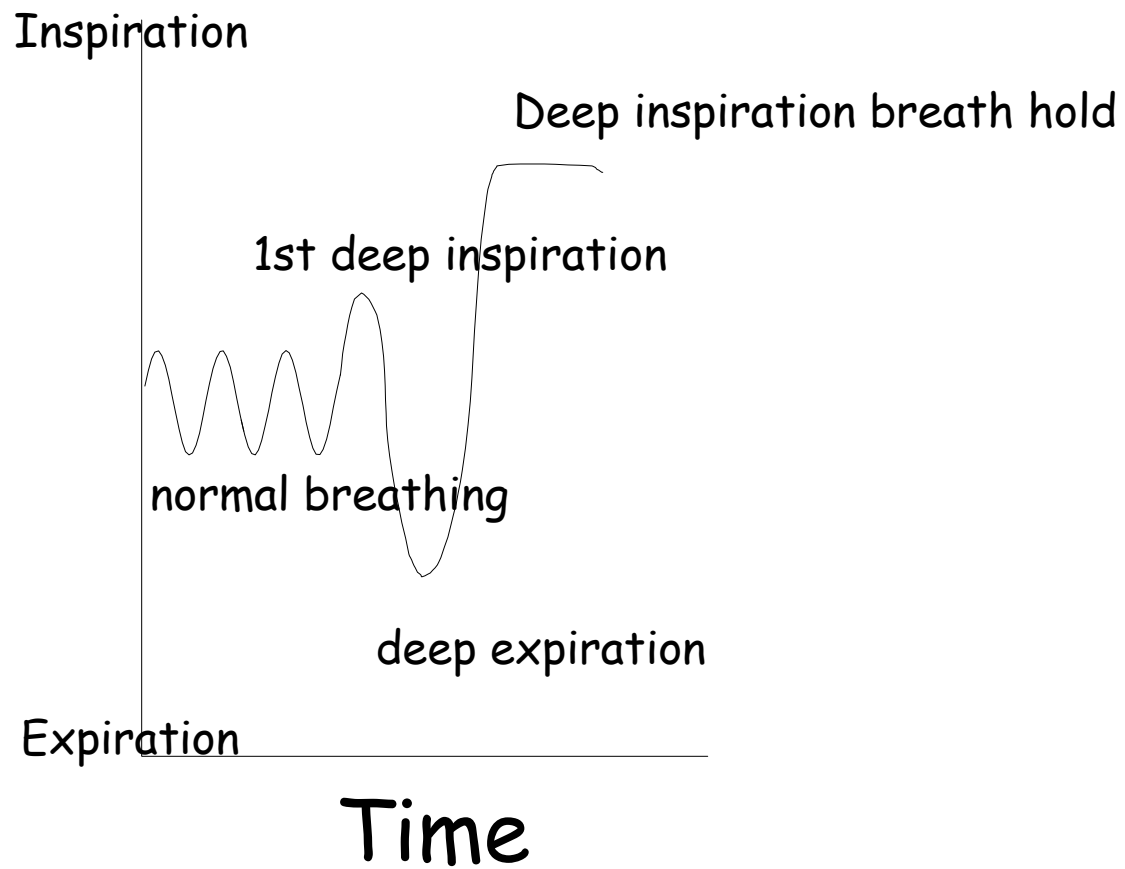


Free Breathing



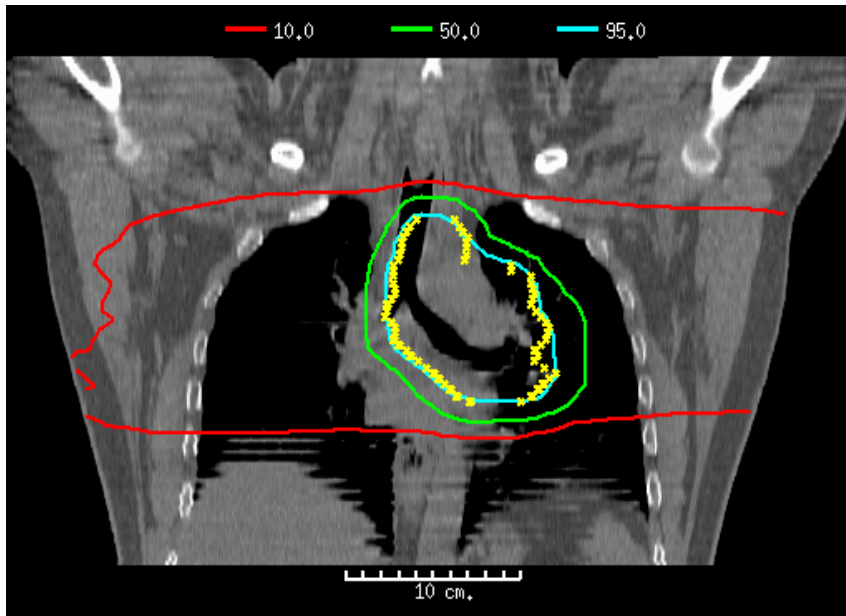
DIBH

# Setup

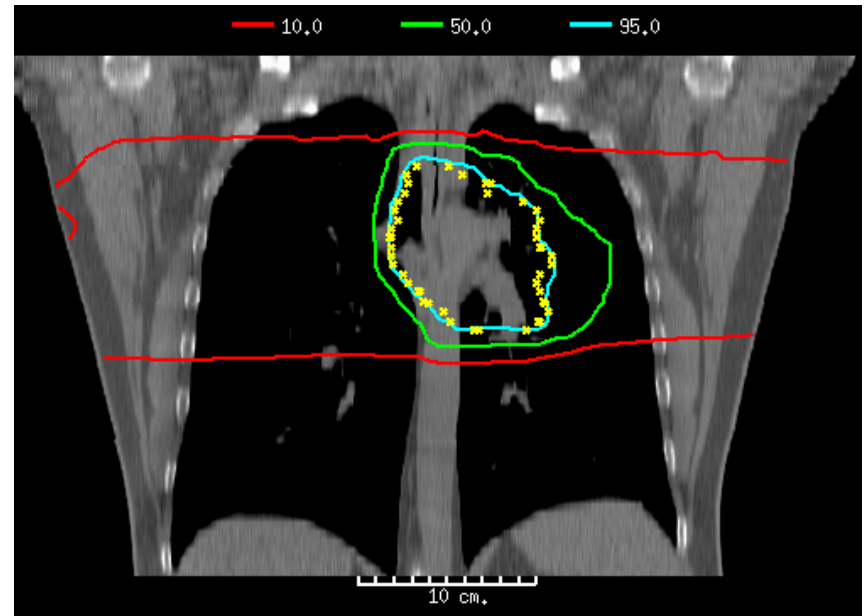


# Planning Comparison

Free Breathing

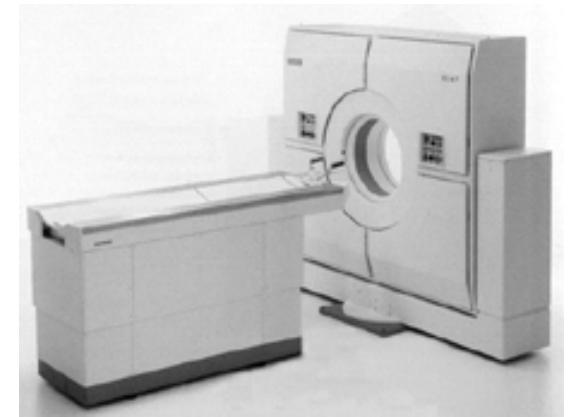


Deep Inspiration



- Less lung within the 10% isodose curve (red line) with deep inspiration

# PET worldwide



- 1600 PET scanners were installed worldwide between 1992 and 2002 -- 1020 in the U.S., 470 in Europe, and 110 in Japan

The number of planned installations for Europe over the next five years is 116. A total of 30 scanners are due to be installed in Italy, 24 in France, 21 in Spain, 8 in the U.K., six in Sweden, five in Finland, and four in Belgium. The number of cyclotrons in Europe in 2001 was 62. A further 22 were planned for the next five years.

# PET/CT

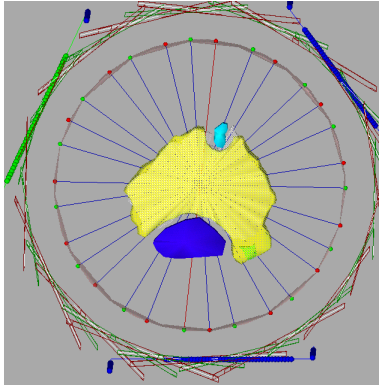


- ~300 installed worldwide since being commercially available in 2001
- More and more will become the standard functional imaging device
- Software or hardware solution
- Advantages of hardware
  - same bed
  - little organ motion
  - improved registration

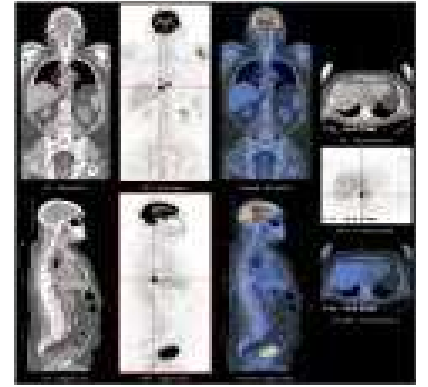
# CT/PET fusion



Available with most RTP systems



# Summary



- **IMRT**
  - First used in Australia late 2000
  - 5(?) RT sites conducting it routinely
  - Many wishing to
- **IGRT**
  - 2(?) with CTs in the bunker
  - Others on order
- **PET**
  - 8 PET scanners in the country (3 old, 5 new)
- **Who's doing what**
  - Liverpool: staging only
  - Austin: just started co-registration
  - PeterMac: about 40 cases per year, with the target volumes determined on the co-registered images