# Medical Applications of Position Sensitive Detectors

Alex Elliott

Department of Clinical Physics

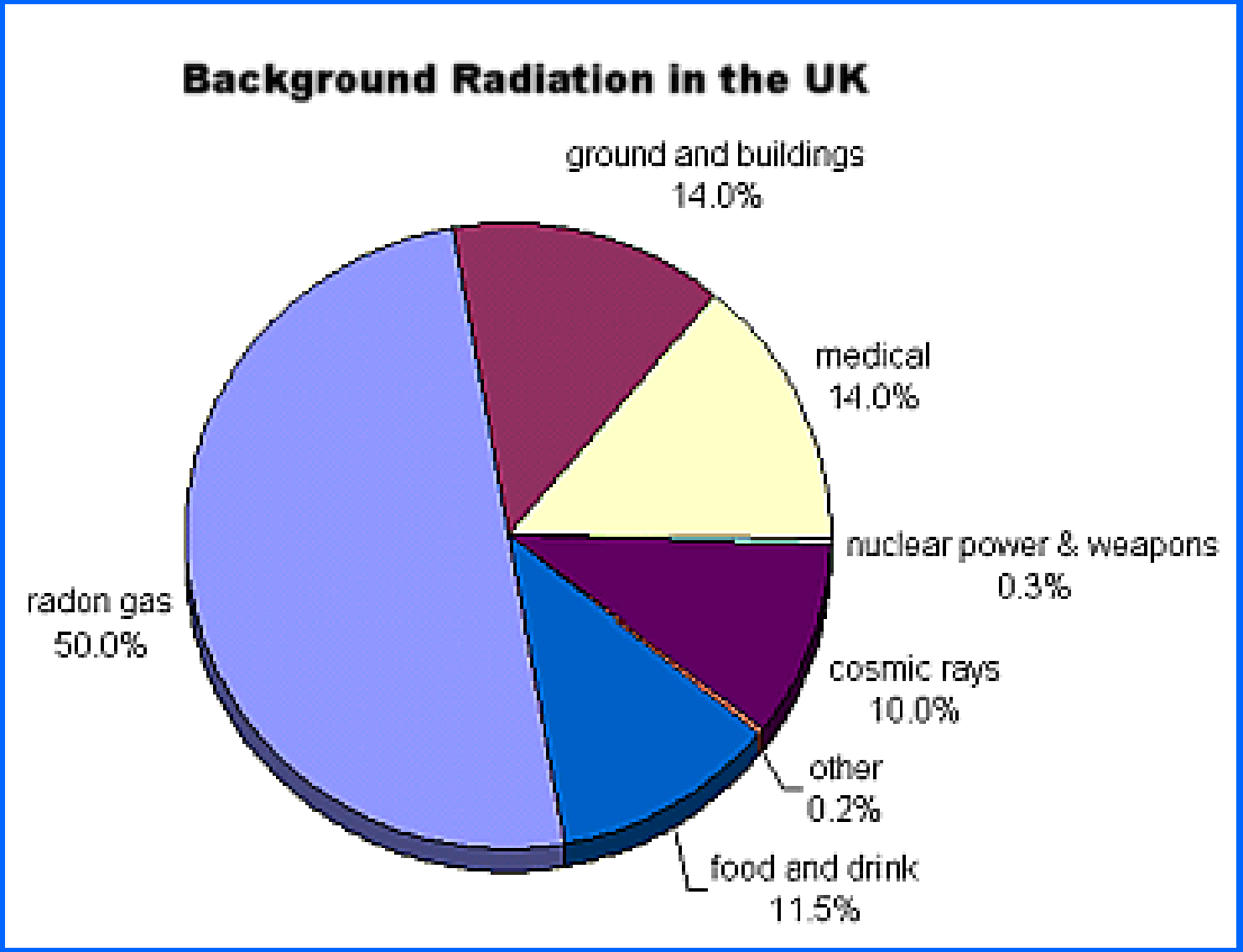
University of Glasgow

# Applications

- Computed Radiology
- Digital Radiology
- Mammography
- Computed Tomography
- Planar Nuclear Medicine/
  Single Photon Emission Computed Tomography
- Positron Emission Tomography
- Megavoltage Imaging

# History of medical imaging

- X-rays - Roentgen, 1895
- Nuclear medicine - Cassen, 1951
- Ultrasound – Donald, 1962
- SPECT - Kuhl, Edwards, 1963
- PET – Ter-Pogossian, 1972
- MR - Lauterbur, Mansfield, Hutchison, 1972
- CT - Hounsfield, 1973


Background Radiation in the UK
ground and buildings
14.0%
medical
14.0%
nuclear power & weapons
0.3%
cosmic rays
10.0%
other
0.2%
food and drink
11.5%
radon gas
50.0%

# Imaging investigations in England 1995-2007

| Year | X-Rays | CT | MRI | Ultrasound | Radio-isotopes | Fluoro-scopy | Total |
|---|---|---|---|---|---|---|---|
| 1995-96 | 18,503,844 | **1,709,244** | 347,817 | 4,031,292 | 467,916 | 1,077,914 | **26,138,027** |
| 1996-97 | 19,167,629 | 1,056,365 | 394,940 | 4,456,816 | 506,412 | 1,232,795 | 26,814,957 |
| 1997-98 | 19,474,590 | 1,172,656 | 473,074 | 4,790,532 | 722,096 | 1,179,979 | 27,812,927 |
| 1998-99 | 19,876,933 | 1,254,474 | 522,138 | 5,018,434 | 699,654 | 1,244,632 | 28,616,265 |
| 1999-00 | 19,967,296 | 1,359,852 | 585,797 | 5,255,330 | 727,255 | 1,256,965 | 29,152,499 |
| 2000-01 | 19,913,022 | 1,488,752 | 632,594 | 5,382,582 | 539,141 | 1,253,847 | 29,209,938 |
| 2001-02 | 19,806,876 | 1,625,304 | 705,706 | 5,571,979 | 537,653 | 1,222,296 | 29,469,814 |
| 2002-03 | 19,512,924 | 1,767,791 | 786,646 | 5,635,358 | 551,423 | 1,295,639 | 29,549,781 |
| 2003-04 | 20,056,669 | 1,992,826 | 857,550 | 5,937,383 | 582,742 | 1,221,102 | 30,648,272 |
| 2004-05 | 19,818,330 | 2,141,652 | 944,935 | 6,029,104 | 560,337 | 1,190,487 | 30,684,845 |
| 2005-06 | 20,585,678 | 2,481,571 | 1,118,487 | 6,469,396 | 623,532 | 1,209,029 | 32,487,693 |
| 2006-07 | 21,011,234 | **2,728,119** | 1,257,972 | 6,715,486 | 588,638 | 1,249,161 | **33,550,610** |

# Preliminary US Results (2006)

| | Number procedures | % | Collective dose (Person-Sv) | % | Per capita (mSv) |
|---|---|---|---|---|---|
| Radiography | 276 million | 52 | 182,000 | 19 | 0.6 |
| Interventional | 13 million | 2 | 112,000 | 12 | 0.4 |
| CT | 67 million | 12 | 440,000 | 46 | 1.45 |
| Mammography | 34 million | 6 | 3,300 | < 0.5 | 0.01 |
| Dental | 125 million | 23 | 2,300 | <0.5 | 0.01 |
| Nuclear Medicine | 19 million | 4 | 220,000 | 23 | 0.7 |
| Radiotherapy | 1 million pts | NA | NA | -- | -- |

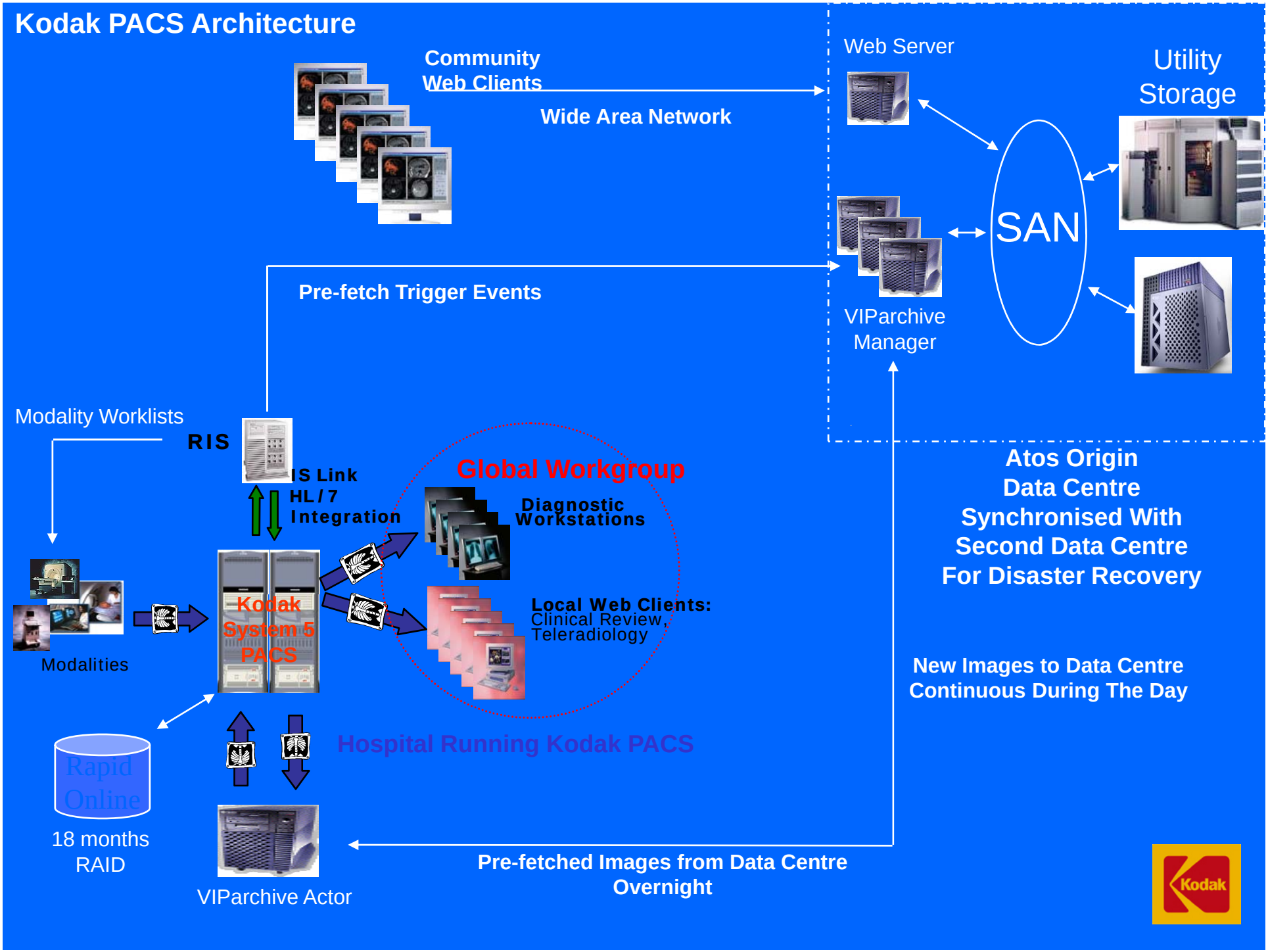
# Detector qualities

- High absorption efficiency
- High conversion efficiency
- Low ‘dark current’
- Rapid decay time
- Good energy resolution
- Good spatial resolution
- Rapid processing

# Radiation Damage

A number of cases of significant radiation damage have been reported as a result of interventional radiology and cardiology procedures

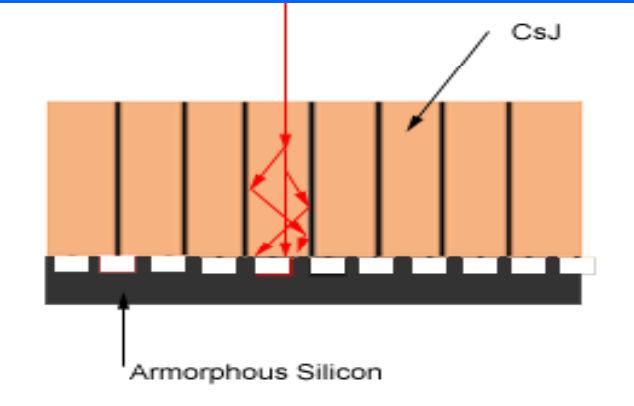
Appearance after 6-8 weeks and after 18-21 months


Kodak PACS Architecture
Community
Web Clients
Wide Area Network
Web Server
Utility
Storage
SAN
Pre-fetch Trigger Events
VIParchive
Manager
Modality Worklists
RIS
IS Link
HL/7
Integration
Global Workgroup
Diagnostic
Workstations
Kodak
System 5
PACS
Local Web Clients:
Clinical Review,
Teleradiology
Modalities
Hospital Running Kodak PACS
Rapid
Online
18 months
RAID
VIParchive Actor
Atos Origin
Data Centre
Synchronised With
Second Data Centre
For Disaster Recovery
New Images to Data Centre
Continuous During The Day
Pre-fetched Images from Data Centre
Overnight
Kodak

# Planar X-ray (Computed/Digital Radiology)

- Relies on contrast from electron density
- Photon energy 60-140keV
- Radiation dose per view
  - limits number of images
- Spatial resolution ~ 0.1mm
- Temporal resolution ~ 10ms

# Detector Technology

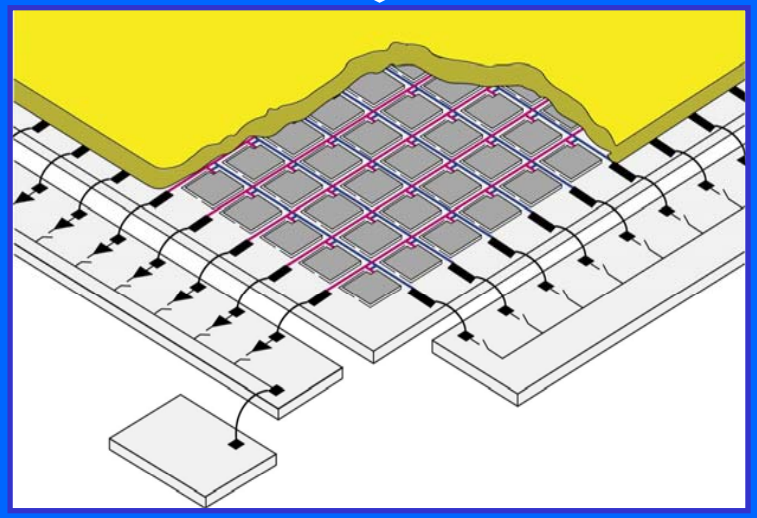



X-ray absorption:

- CsI converts X-ray to light
- CsI needle structure avoids light scatter
- photo diodes convert light to charges
- charges stored in capacitors

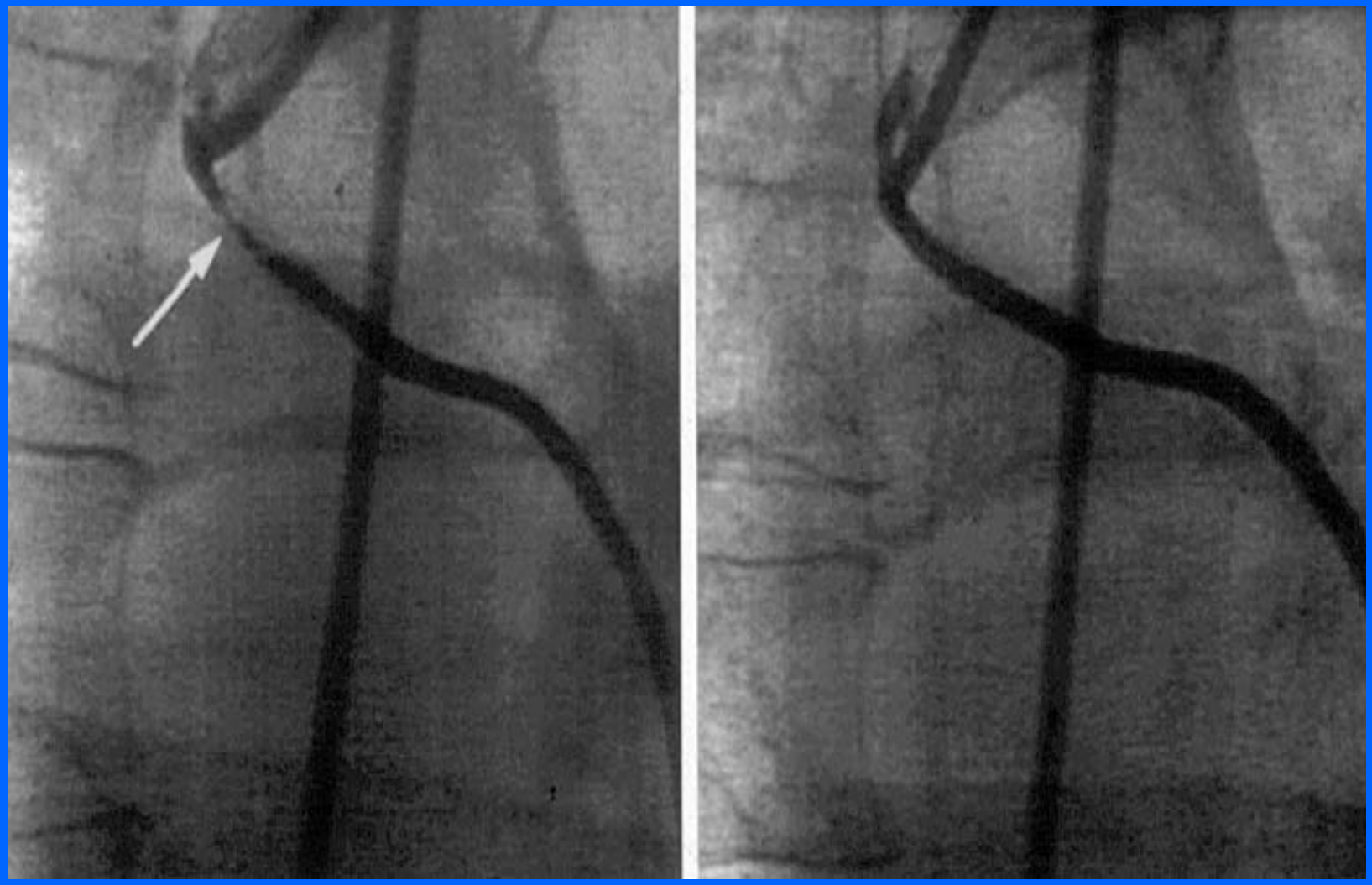
Image readout:

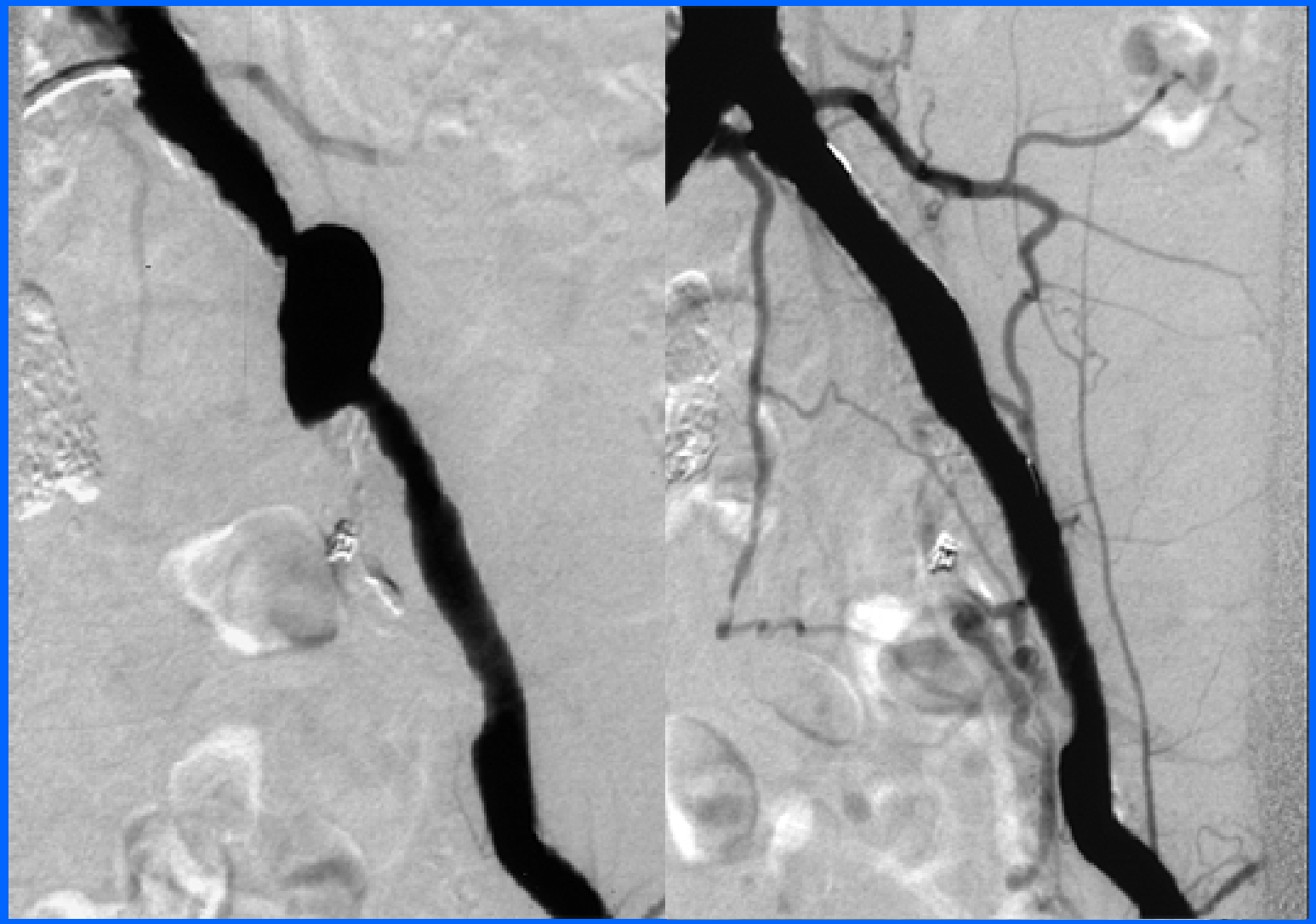
- multiplexed high speed readout
- ultra low noise electronics
- no need for water cooling
- fast transmission to operating console



# Detector Technology

| | Trixell | GE | Hologic | Canon |
|---|---|---|---|---|
| **Type** | Amorphous silicon | Amorphous silicon | Amorphous selenium | Amorphous silicon |
| **Active Size [cm]** | 43 x 43 | 41 x 41 | 35 x 43 | 43 x 43 |
| **Pixels** | 9 million | 4 million | 7.86 million | 7.2 million |
| **Pixel pitch [µm]** | 143 (3.5 lp/mm) | 200 (2.5 lp/mm) | 139 (3.6 lp/mm) | 160 (3.1 lp/mm) |
| **Gray scale** | 16384 (14 bit) | 16384 (14 bit) | 4096 (12 bit) | 4096 (12 bit) |
| **Tomography** | yes | no | no | no |
| **Dose range** | 400 – 800 speed | 400 speed | 200 – 400 speed | 200 speed |
| **Active cooling** | no | yes | no | no |





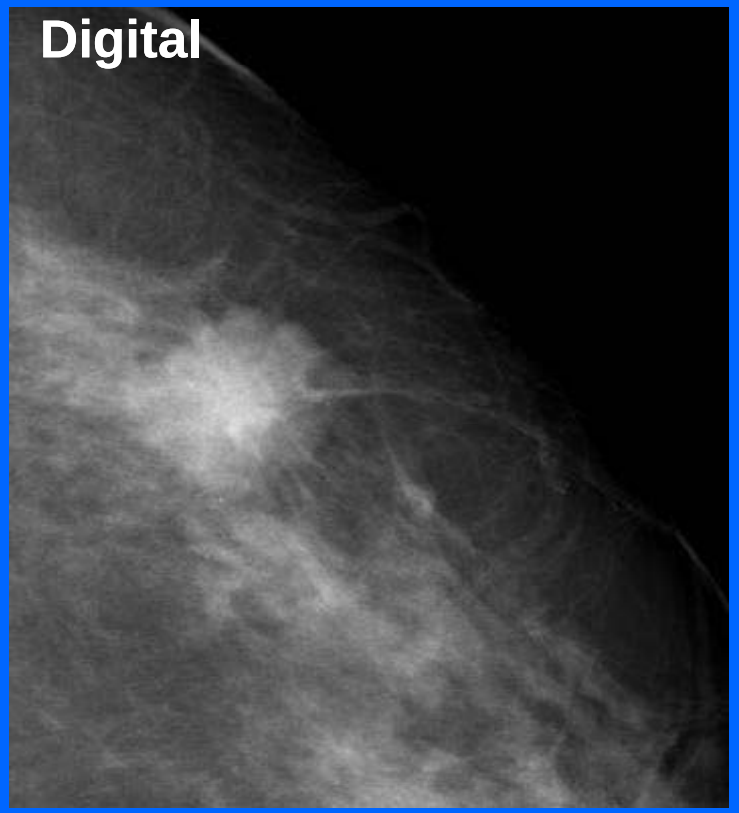
# Mammography

- Photon energy 25-40keV
- High resolution
- High sensitivity

# Mammography Detector

- Area 31 x 24 cm
- Pixel pitch 100µm
- Dynamic range 14 bits
- Image size 3062 x 2394 pixels (14MB)
- Scintillator optimised CsI
- Closed loop liquid cooling

# Mammography comparison


**Better contrast in digital : enables visualisation of the whole lesion**

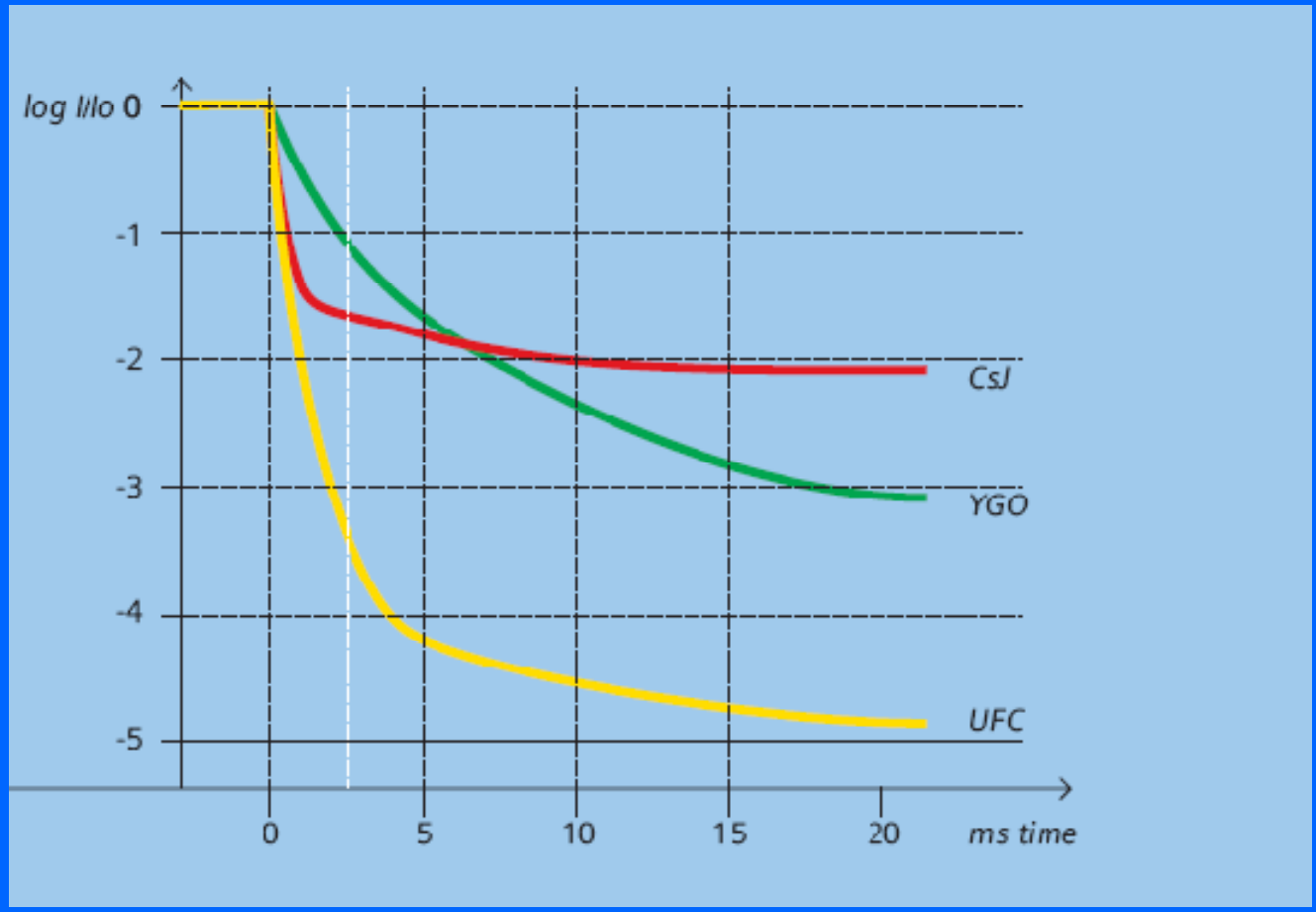
# CT

- Relies on contrast from electron density
- Photon energy 60-140keV
- Radiation dose per view
- Spatial resolution ~ 0.1mm
- Temporal resolution ~ 0.5s

# CT data flow

- 16-slice system
- 10K measurement channels
- 10M measured values per rotation
- Gb/s data rates

# Decay time and afterglow



# Scintillator Properties

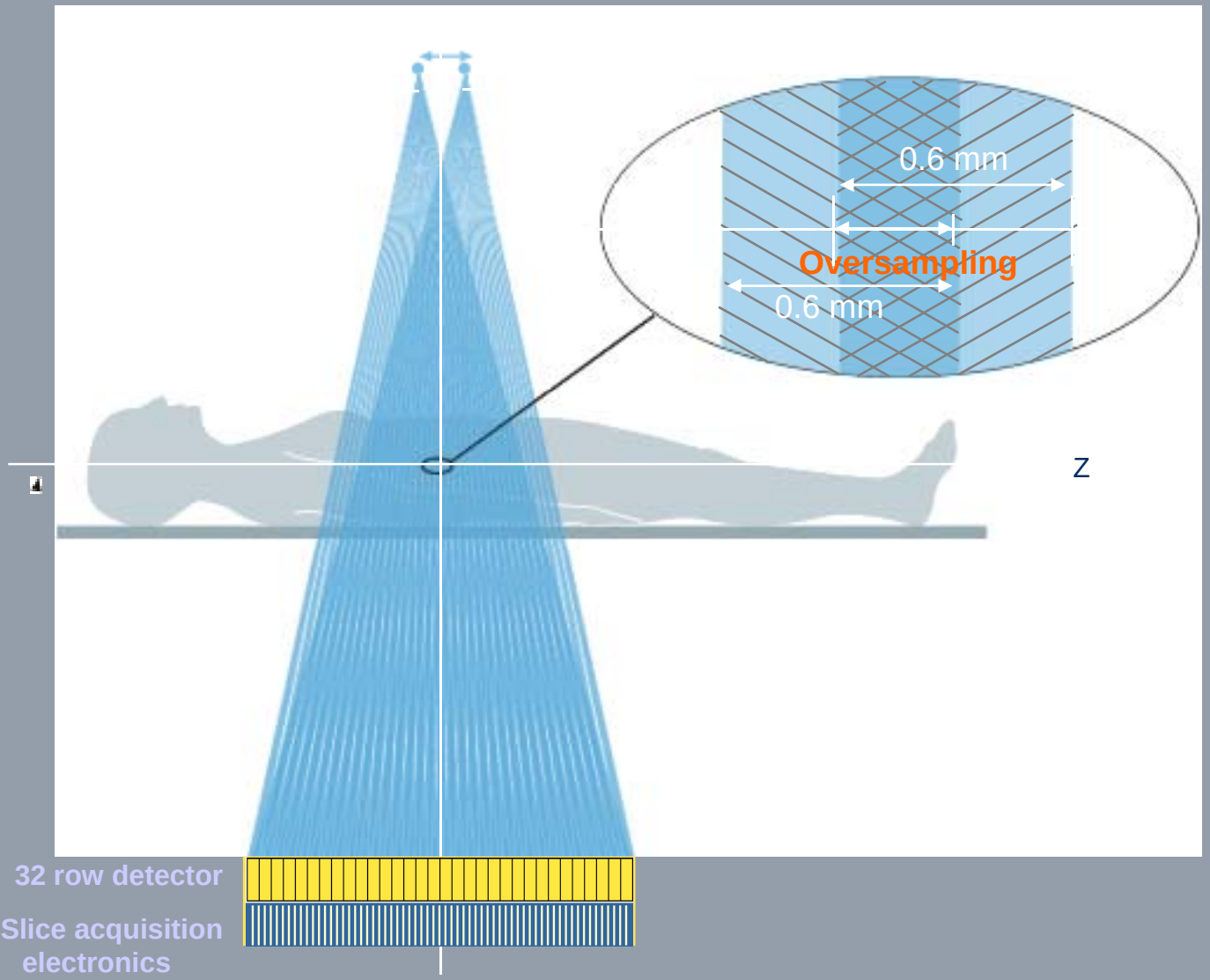
| | CsI | GOS | $CdWO_4$ |
|---|---|---|---|
| Density ($g.cm^{-3}$) | 4.51 | 7.34 | 7.9 |
| Relative light output | 100 | 77 | 31 |
| Decay time (μs) | 0.98 | 2.5 | 8.9 |
| Afterglow @ 30ms (ppm) | 100 | 32 | 160 |
| Drift (120keV, 15000mAs, 60s) | 2% | 0.2% | 0.4% |

# Doped GOS

- Supersaturated solution heated to produce crystallites
- Resulting powder sintered
- Cut into wafers
- Wafers structured by orthogonal saw cuts
- Interstitial gaps filled with reflecting polymer

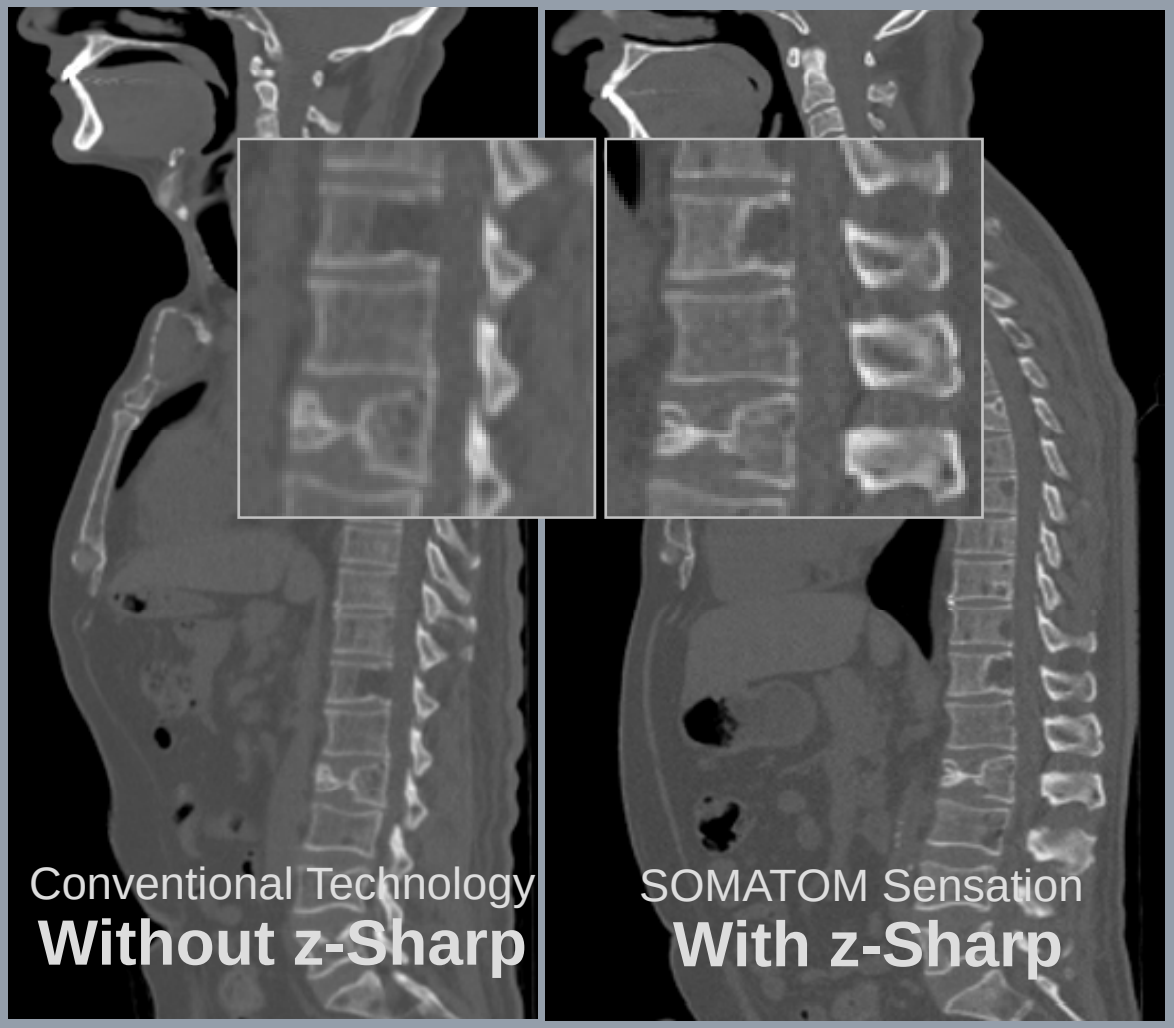
# Image quality
# Z-sharp Technology

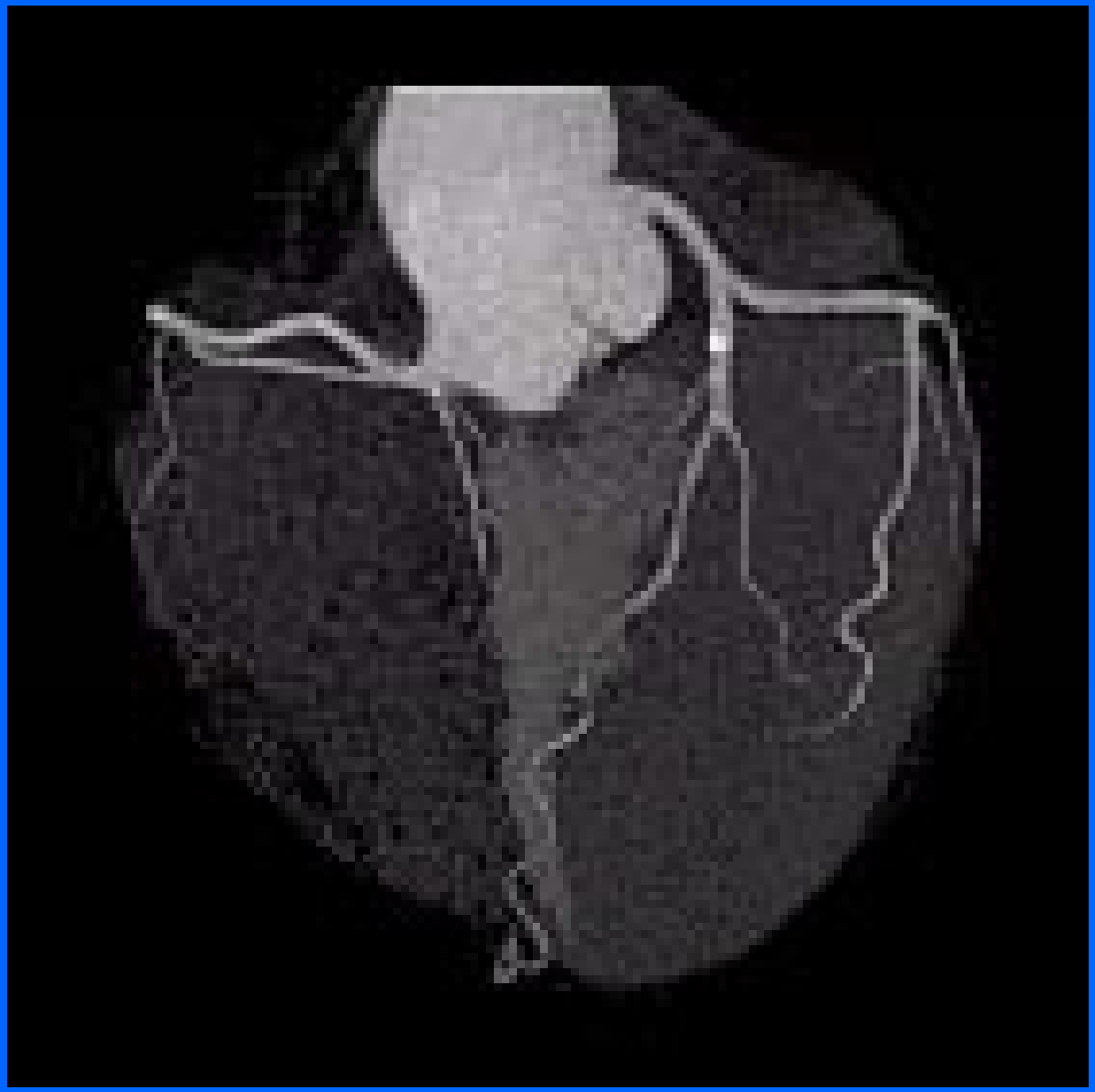
SIEMENS

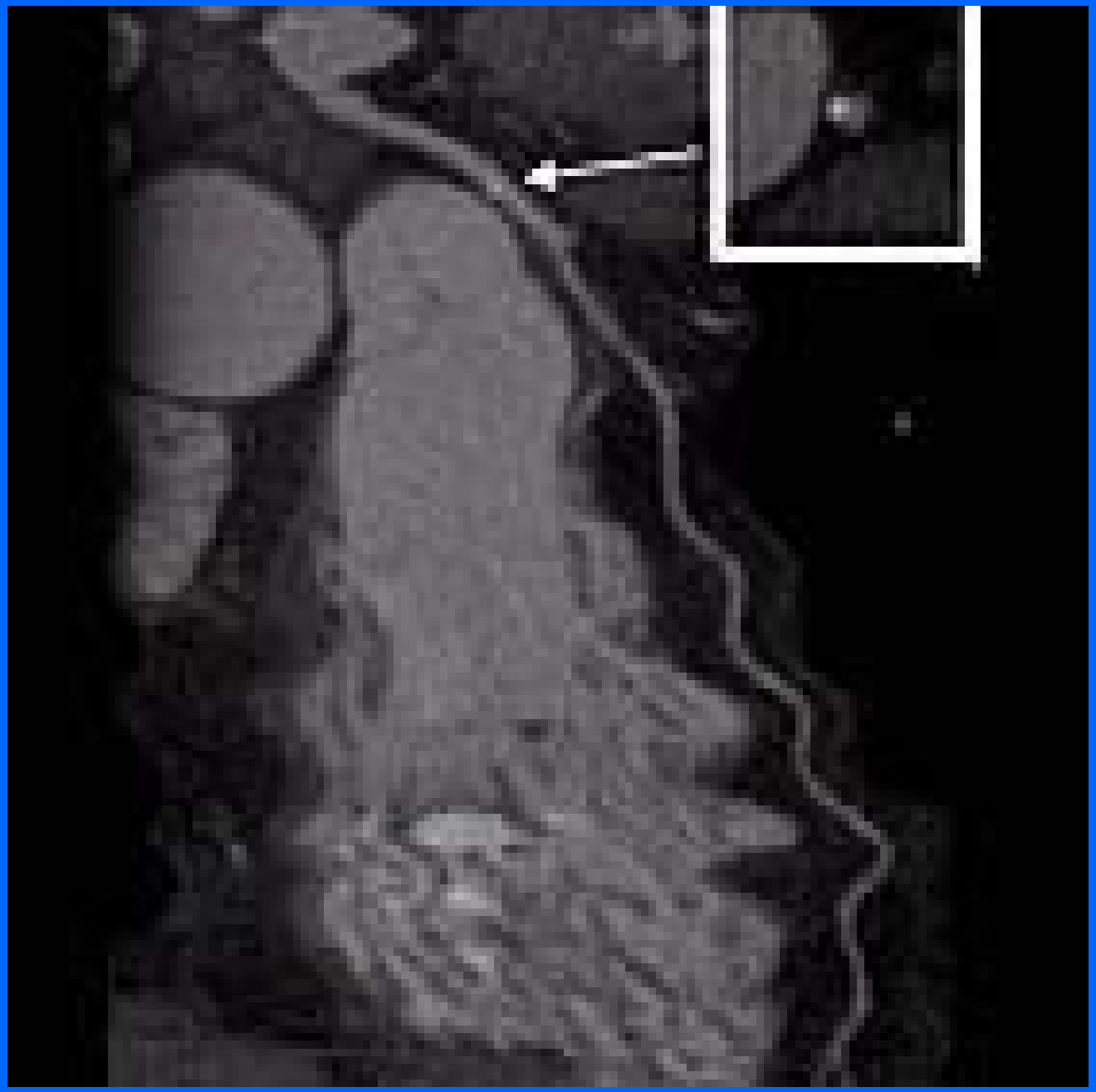


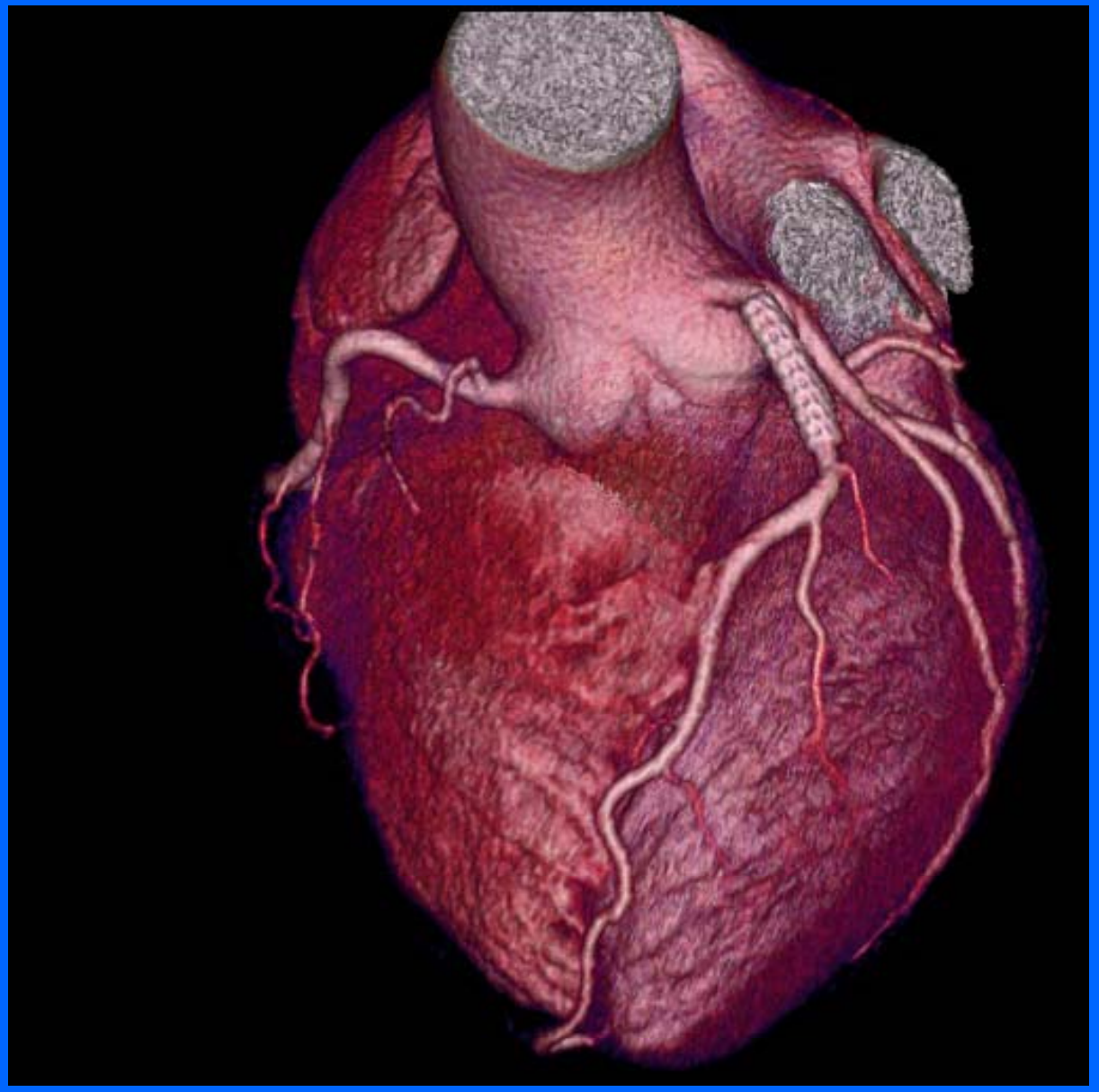
SIEMENS

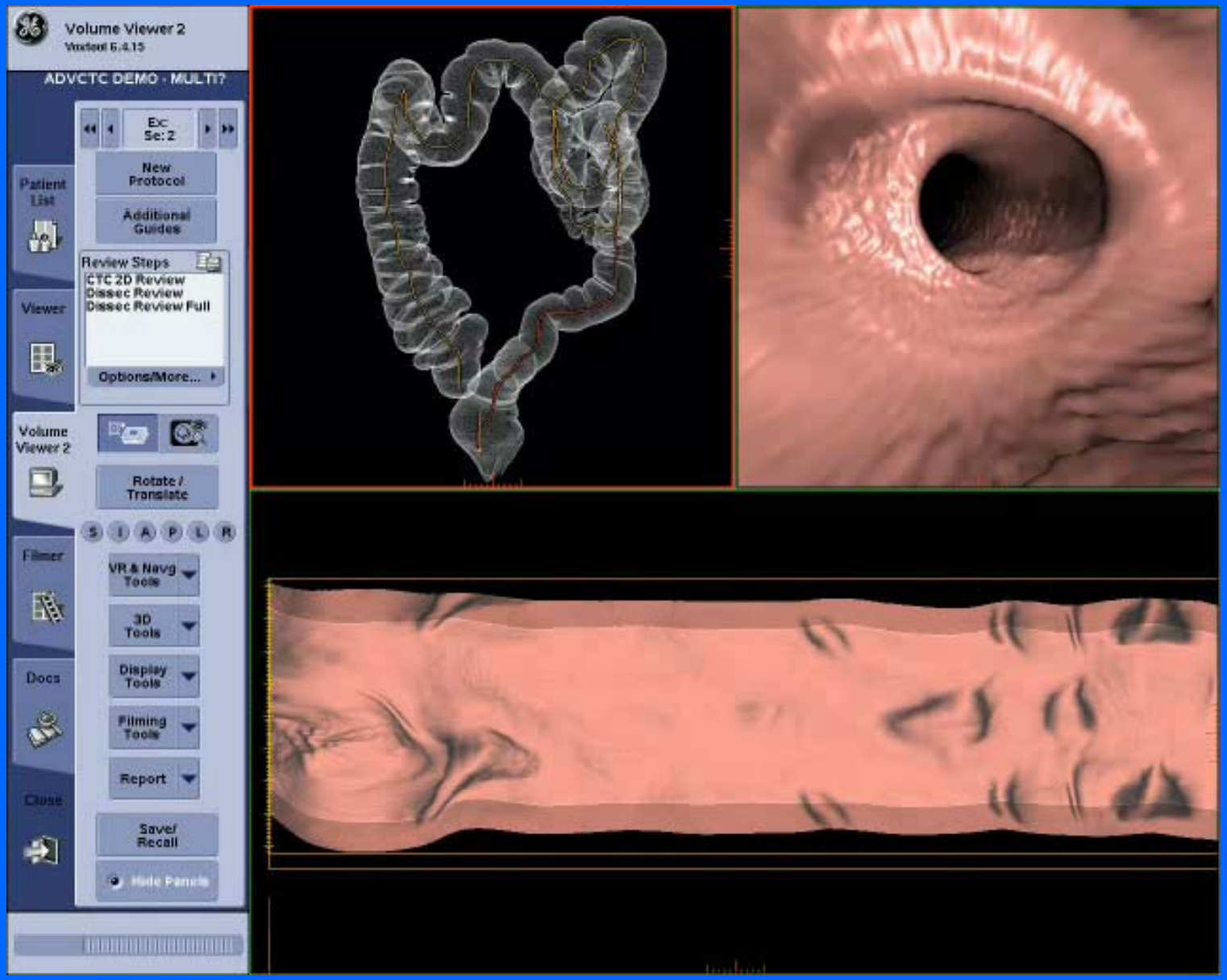
# Z-sharp Technology










Volume Viewer 2
ADVCTC DEMO - MULTI?
Exc
Se: 2
New Protocol
Additional Guides
Review Steps
CTC 2D Review
Dissec Review
Dissec Review Full
Options/More...
Patient List
Viewer
Volume Viewer 2
Filmer
Docs
Close
Rotate / Translate
S I A P L R
VR & Navg Tools
3D Tools
Display Tools
Filming Tools
Report
Save/ Recall
Hide Panels

# COMARE 12

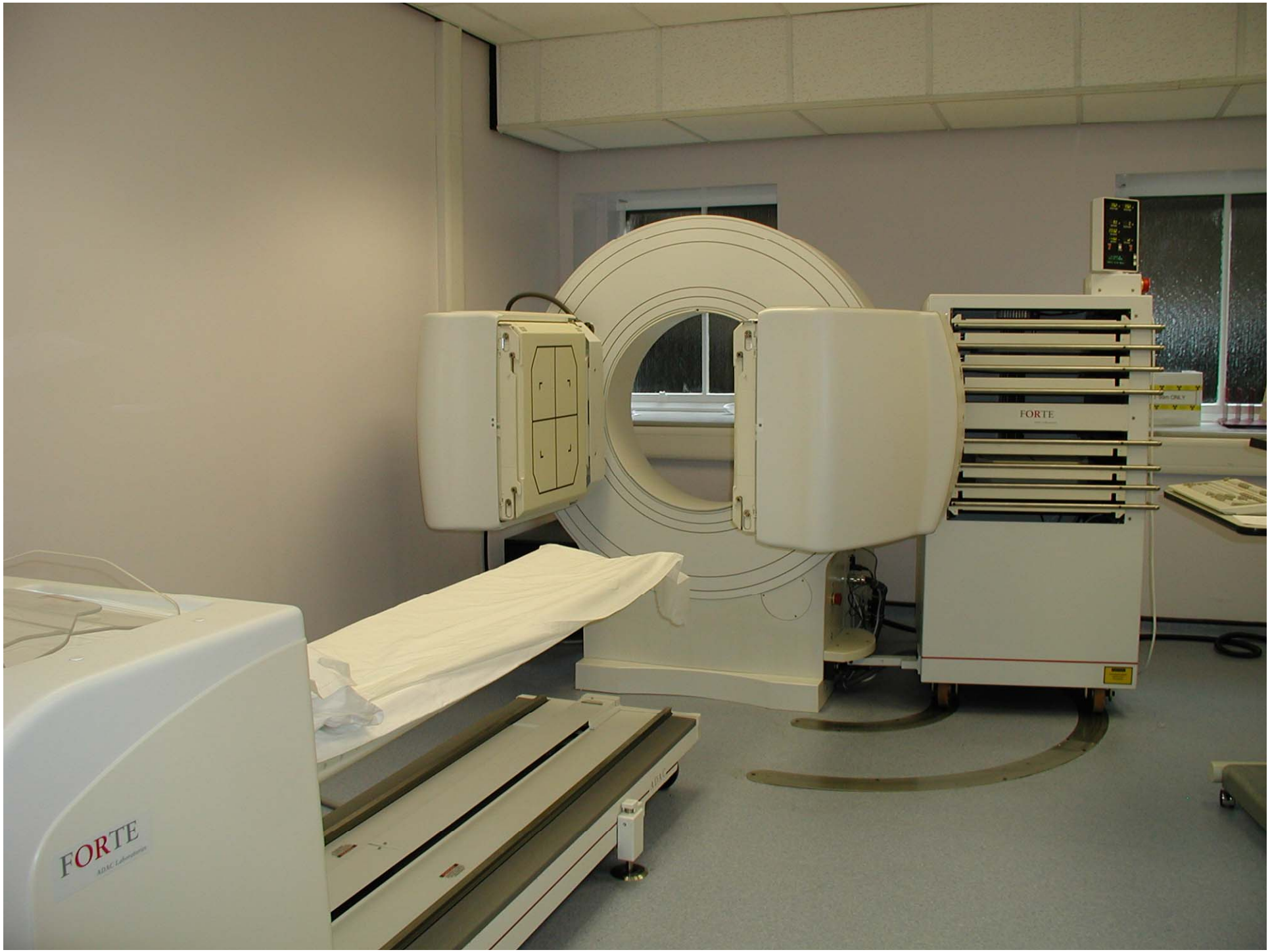
**The impact of personally initiated X-ray Computed Tomography scanning for the health assessment of asymptomatic individuals**

# Recommendations 7-9
# CT of the lung, heart and colon

- Lung CT scanning of the asymptomatic individual cannot be justified and should not be made available.
- CT scanning to determine coronary calcification should be undertaken only on intermediate risk individuals, unless referred by a specialist. Scans should not be performed more than once every three years.
- Screening for colorectal cancer using CT colonography outside of NHS screening programmes should only be undertaken over the age of 50, and not more than once every 2- 3 years. Individuals at high risk should be assessed by specialists. CT colonography screening of high-risk individuals should be part of a multidisciplinary care package.

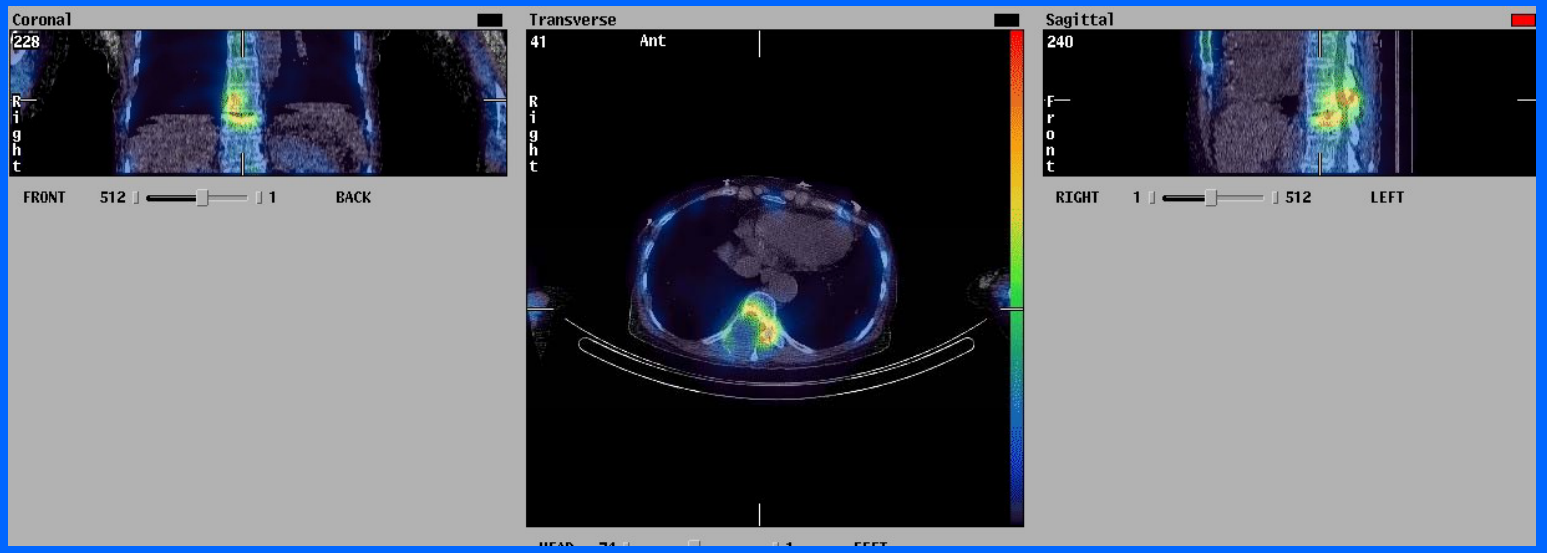
# Nuclear medicine/SPECT

- Requires radiolabel
- Photon energy 80-400keV
- Radiation dose per administration
- Spatial resolution ~ 5-10mm/6-12mm
- Temporal resolution ~ 50ms/2-10min

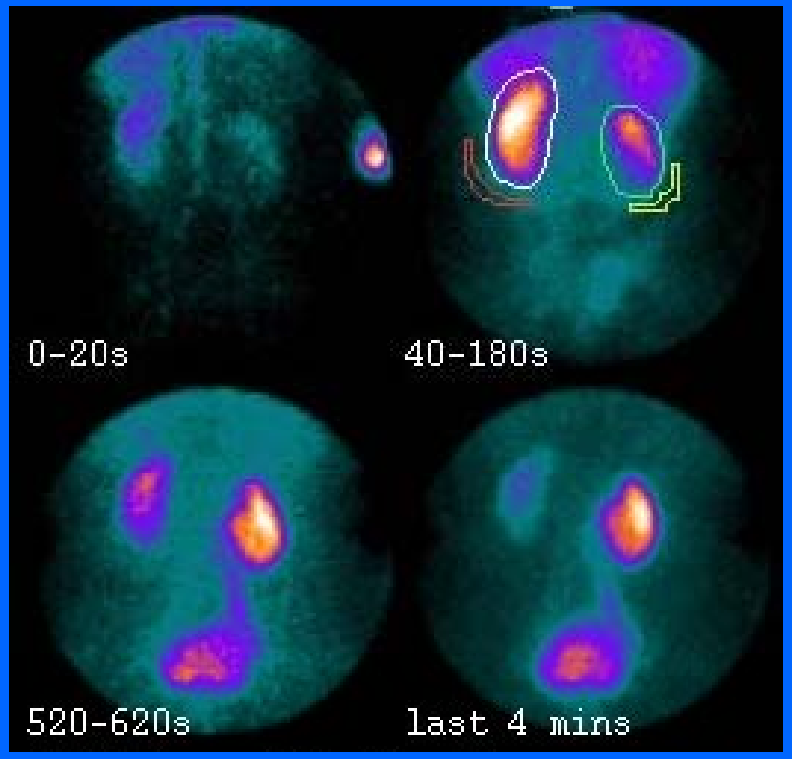

FORTE
FORTE

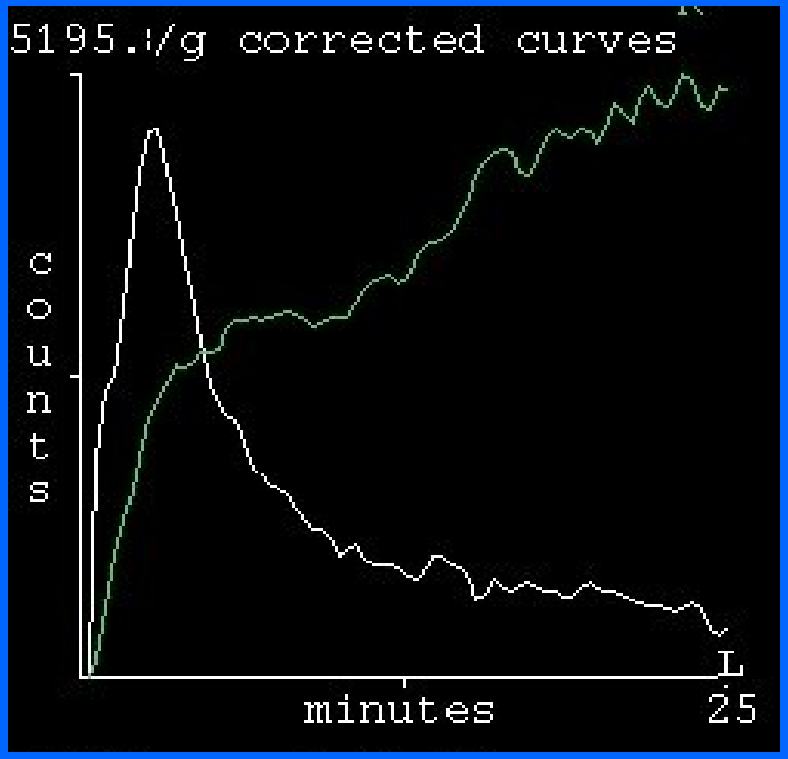
# Bone Scan – Metastatic Disease

# Cord Compression



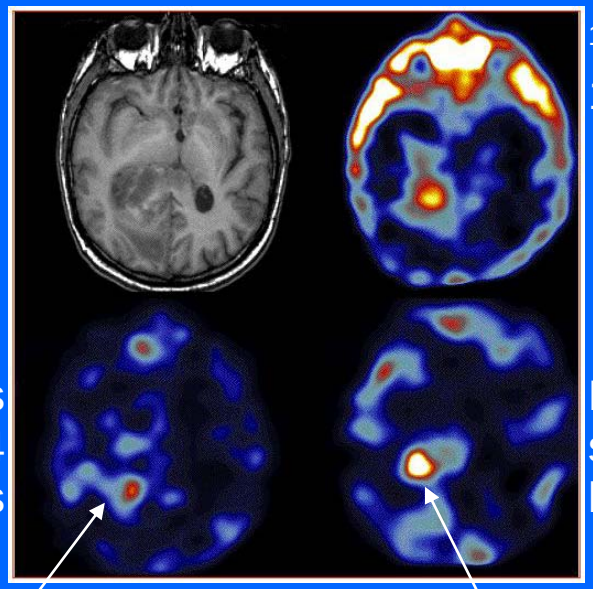
# Obstructed kidney



# Use of $^{123}$I-FIAU to image the distribution of replicating HSV1716 Herpes Simplex Virus in the treatment of glioma

T2 MRI



$^{123}$I-FIAU at 1.5 hours

Pre-virus scan at 24 hours

Post-virus scan at 24 hours

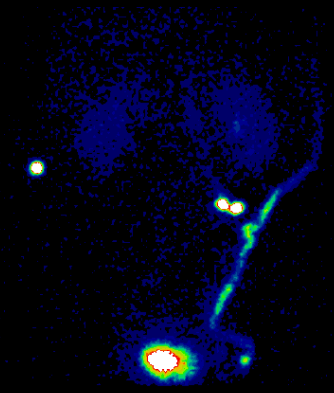
Non-specific washout following uptake through the damaged blood brain barrier

Increased retention at 24 hours consistent with $^{123}$I-FIAU binding to viral thymidine kinase

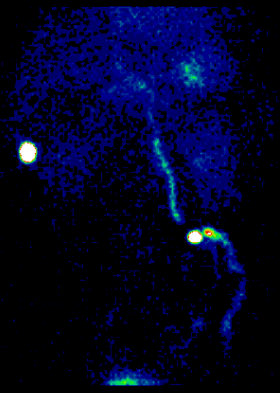
- HSV1716 has been modified to replicate only in rapidly dividing cells
- It can therefore selectively kill tumour cells
- The virus is injected directly into the region of the tumour
- The distribution in-vivo of this virus has to be determined so that delivery can be optimised
- $^{123}$I-FIAU binds to thymidine kinase which is a marker of replicating HSV

# Drug delivery studies

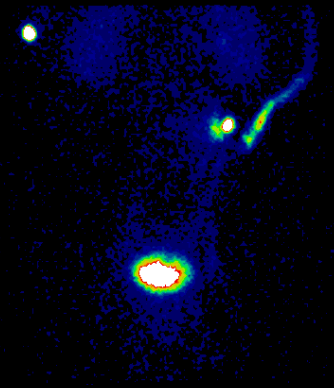
ID needle



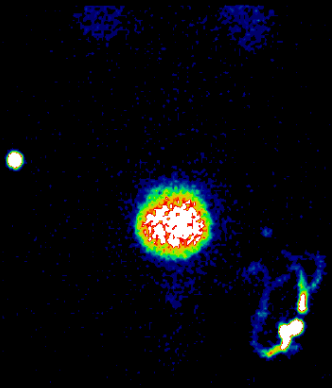
RCS abdomen



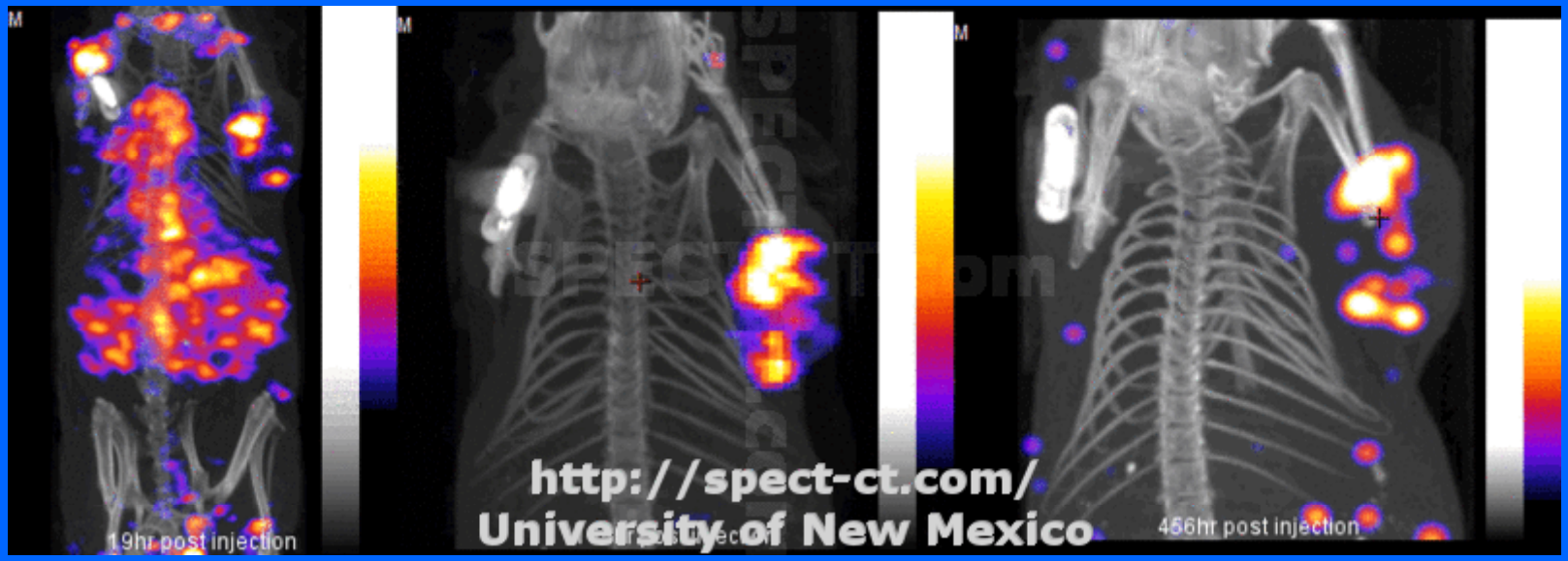
SC



RCS thigh



# NanoSPECT/CT Tumour Marker



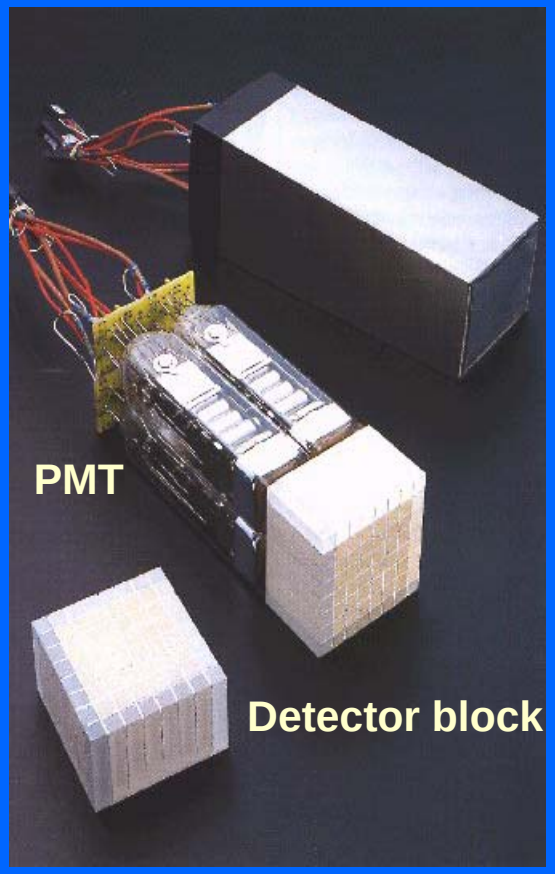
# PET

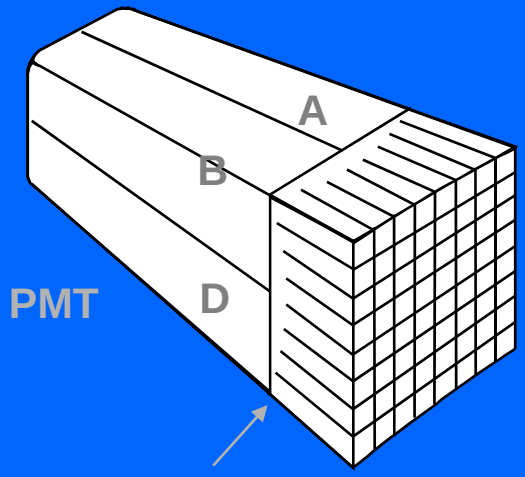
- Requires radiolabel
- Photon energy 511keV
- Radiation dose per administration
- Spatial resolution ~ 3-7mm
- Temporal resolution ~ 2-5min
- On-site/nearby cyclotron (except F-18)

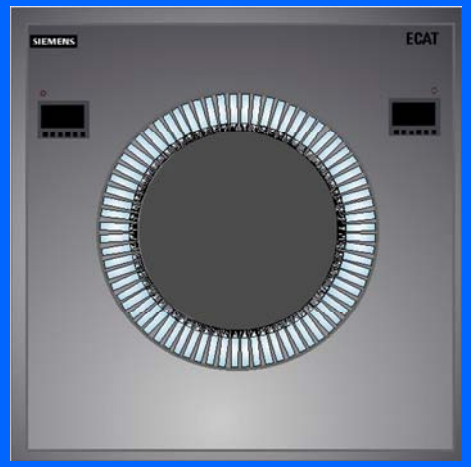
# Scintillator Properties

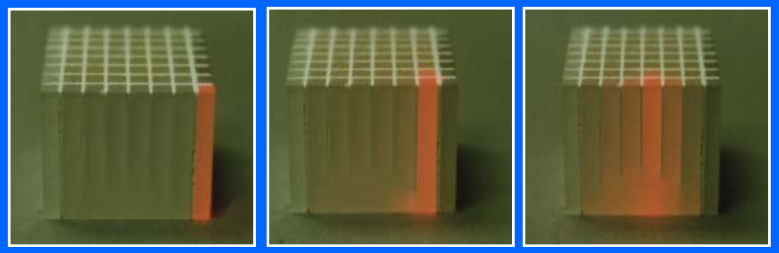
| | NaI | BGO | GSO | LSO | LYSO |
|---|---|---|---|---|---|
| Density (g.cm-3) | 3.7 | 7.1 | 6.7 | 7.4 | 7.1 |
| Effective Z | 51 | 75 | 59 | 66 | 64 |
| Hygroscopic? | Yes | No | No | No | No |
| Rugged? | No | Yes | No | Yes | Yes |
| Decay time (ns) | 230 | 300 | 60 | 40 | 40 |
| Relative light yield | 100 | 15 | 25 | 75 | 83 |

# Scanner Detectors

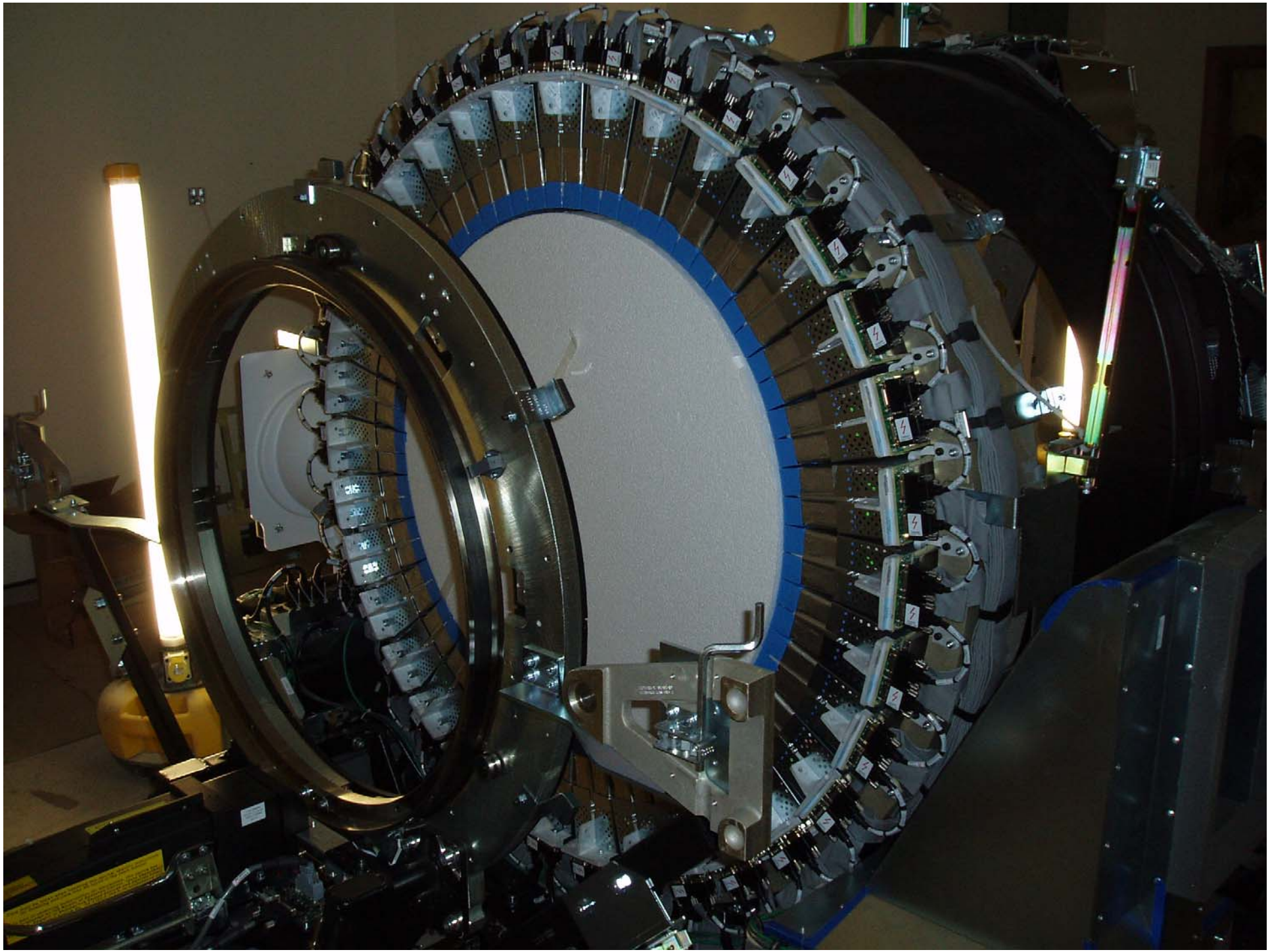


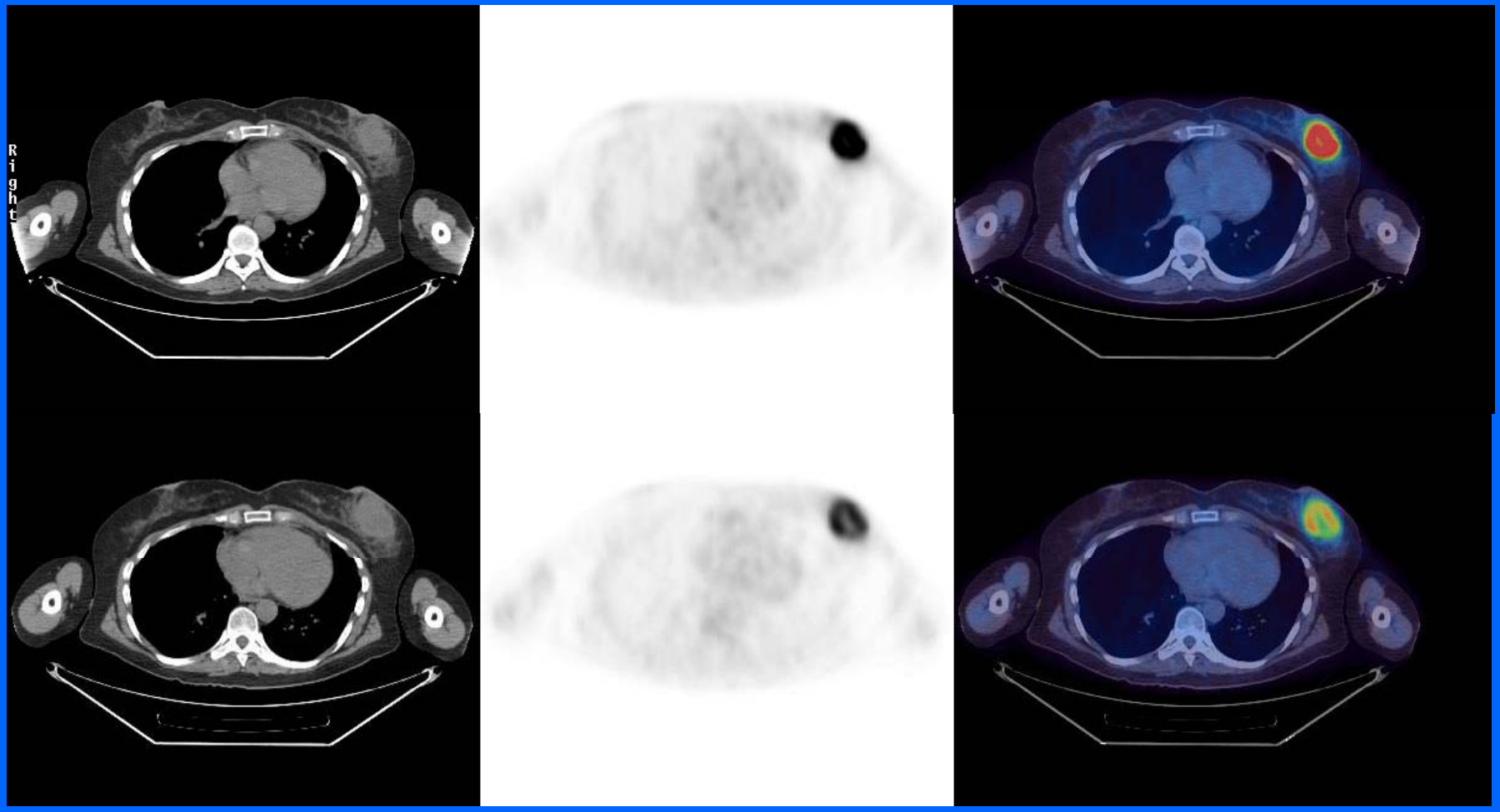



Channeled scintillation light



# Post chemotherapy assessment with PET-CT

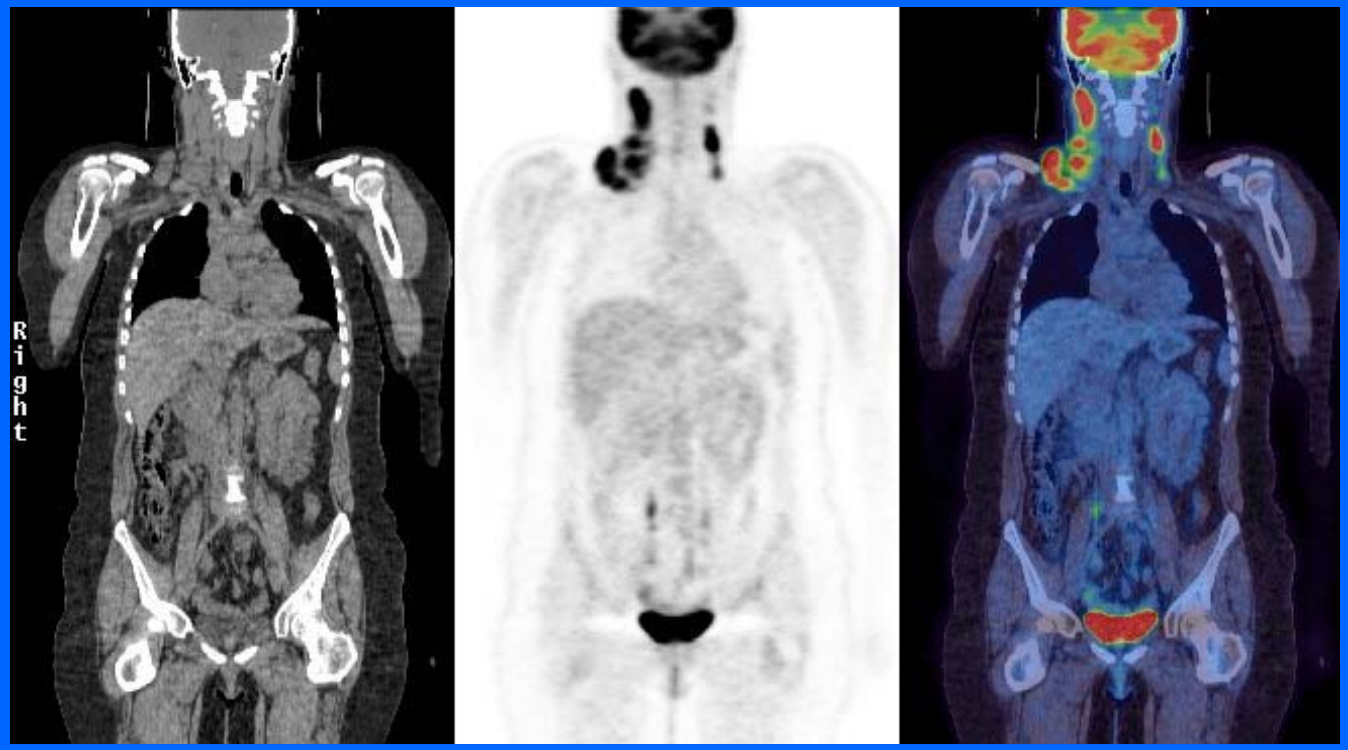



Breast lesion larger post chemotherapy - 42.5x27.5mm to 47.5x27.5mm on CT suggesting progressive disease.

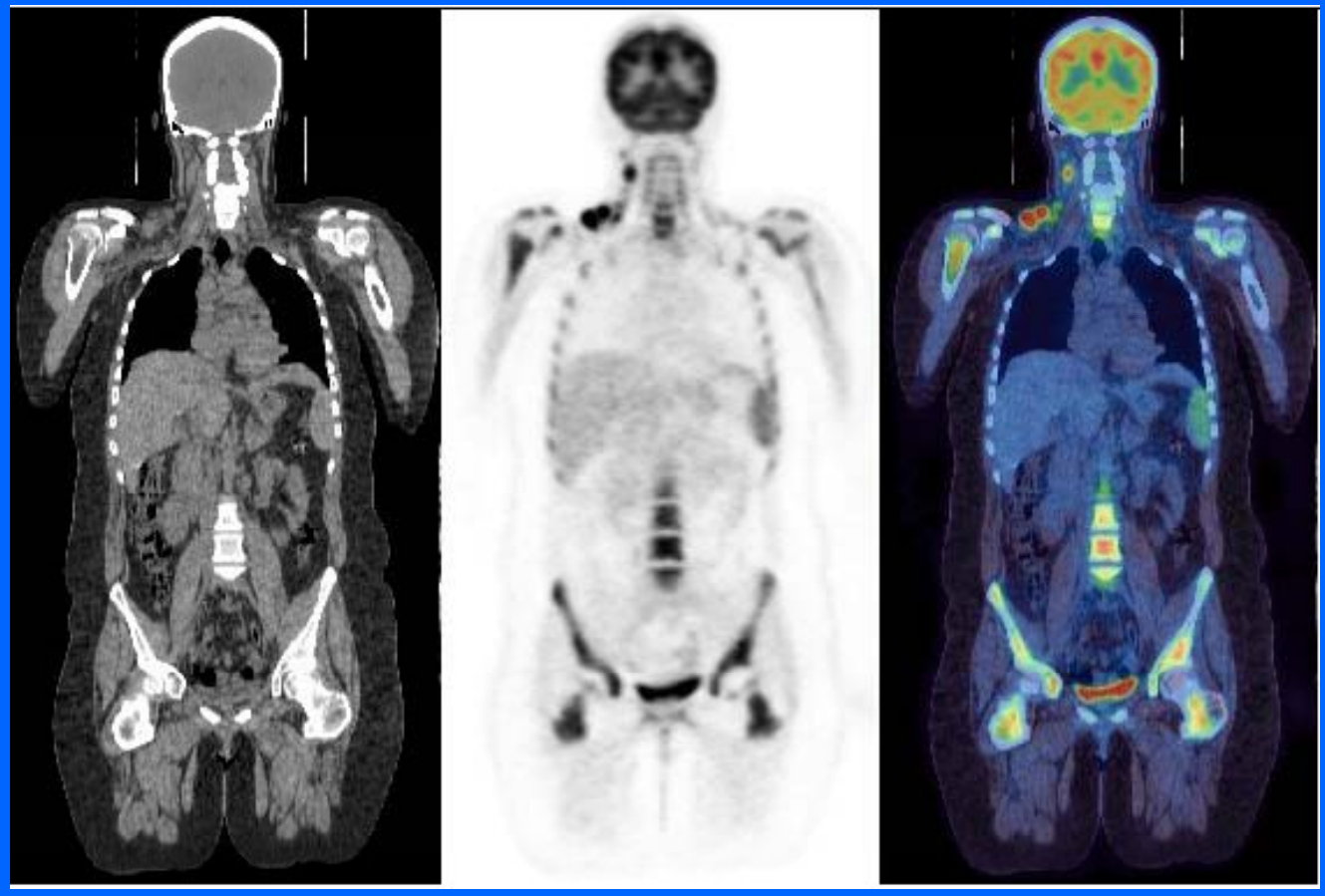
But on PET SUV decreases from 18 to 8 suggesting partial metabolic response. On PET the centre is photopaenic due to central necrosis and this may explain why the lesion is larger.

# Stage IIA HL: pre-treatment

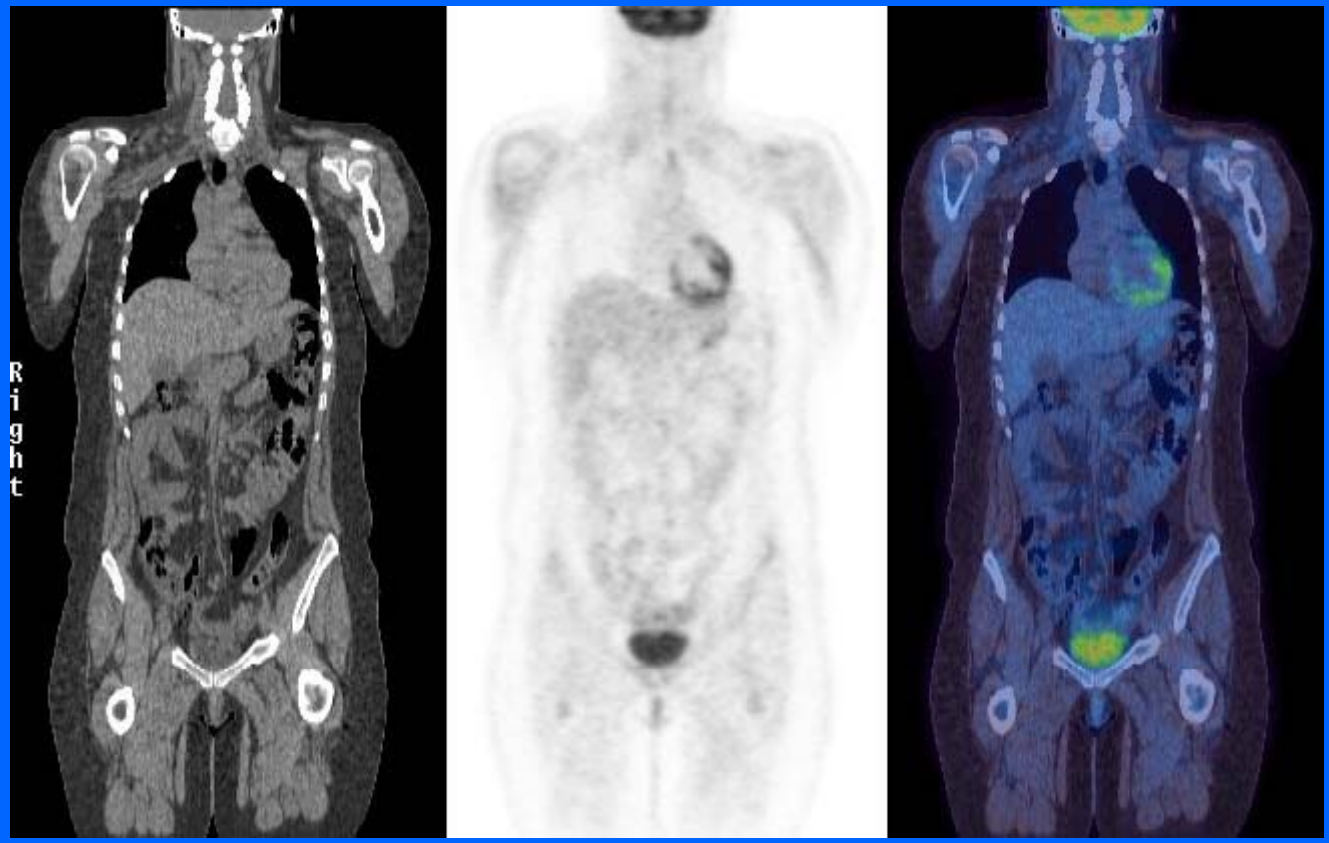
Planned treatment: 4 chemo + RT



# Stage IIA HL: after 2 cycles chemo



# Stage IIA HL: after Radiotherapy



# Detector Improvement (1)

**To improve Spatial Resolution:**

- **Make crystal elements smaller**
- **Make the detector ring diameter larger**

**To improve Sensitivity:**

- **Make crystal elements thicker**
- **Make the detector ring longer**
- **Make the ring diameter smaller**
- **Measure the data differently**

# Detector improvement (2)

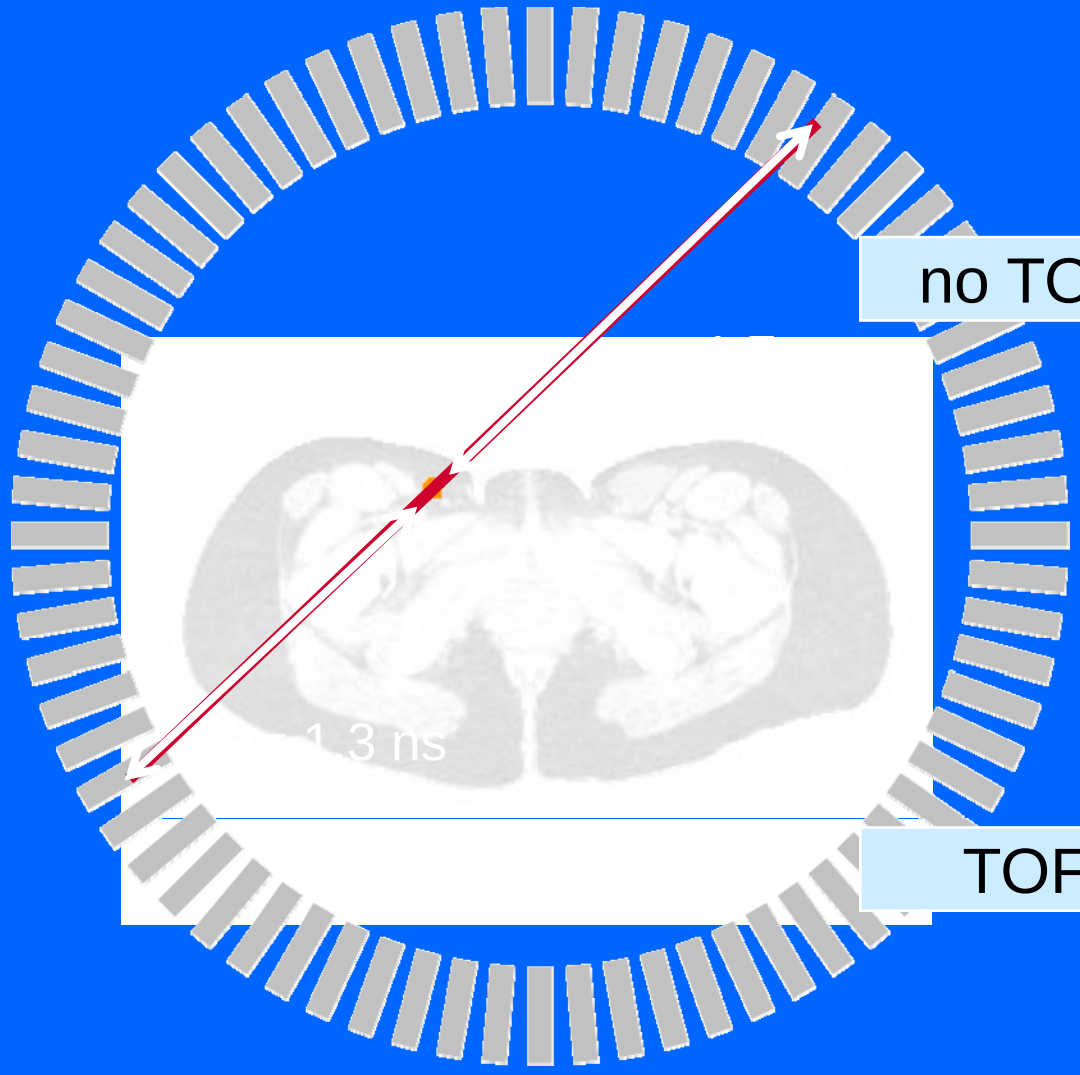
**To improve Scatter fraction:**

- **Find a detector material that has better energy resolution properties**
- **Measure the light generated more accurately**
- **Insert septa in front of the detectors**
- **Shield the detectors more effectively**

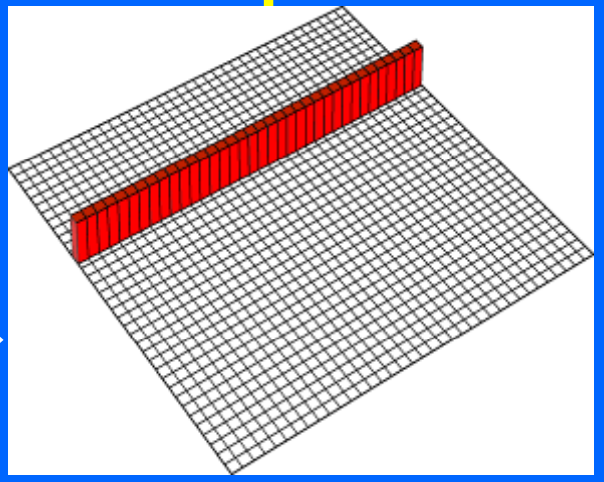
**To improve Random fraction:**

- **Improve accuracy of timing measurements**
- **Insert septa in front of the detectors**
- **Shield the detectors more effectively from radiation originating outside the FoV.**

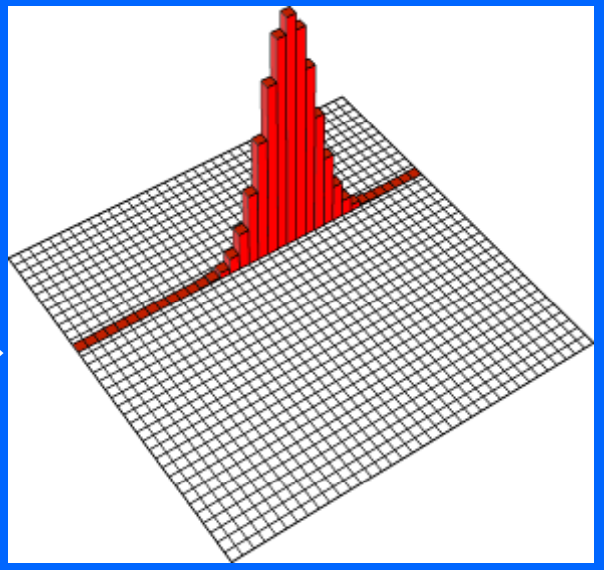
# Time-of-Flight – The Principle




no TOF



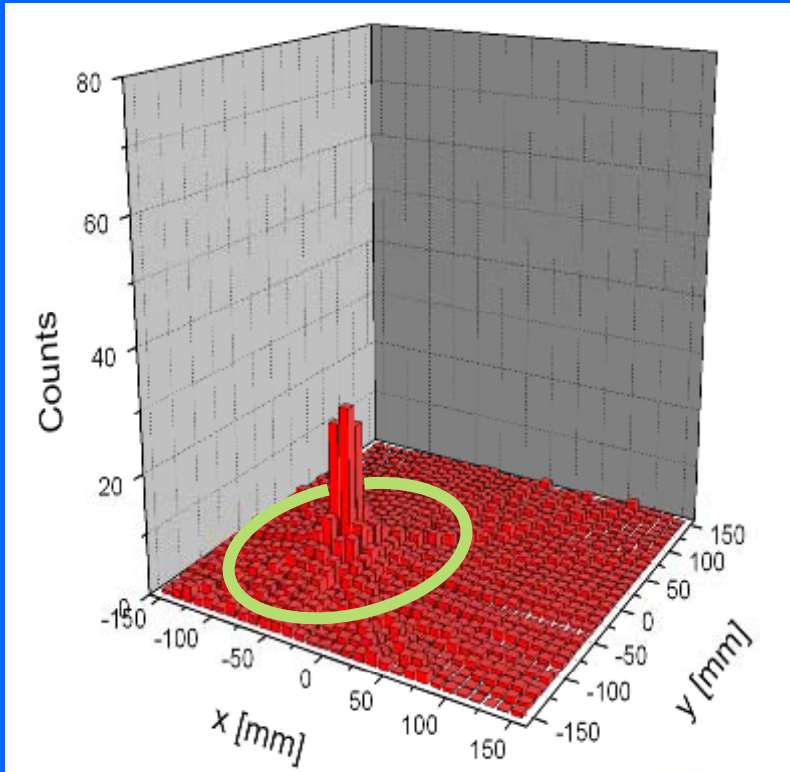
TOF



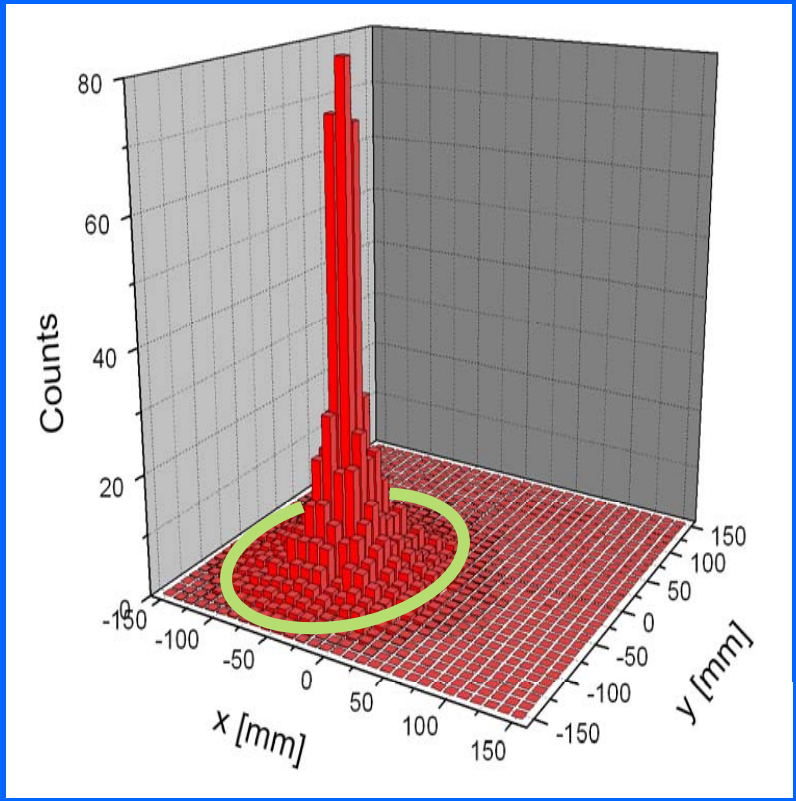
# Noise Propagation in the Reconstruction

Backprojecting several events (no filtering)…

Conventional PET




Time-of-Flight PET

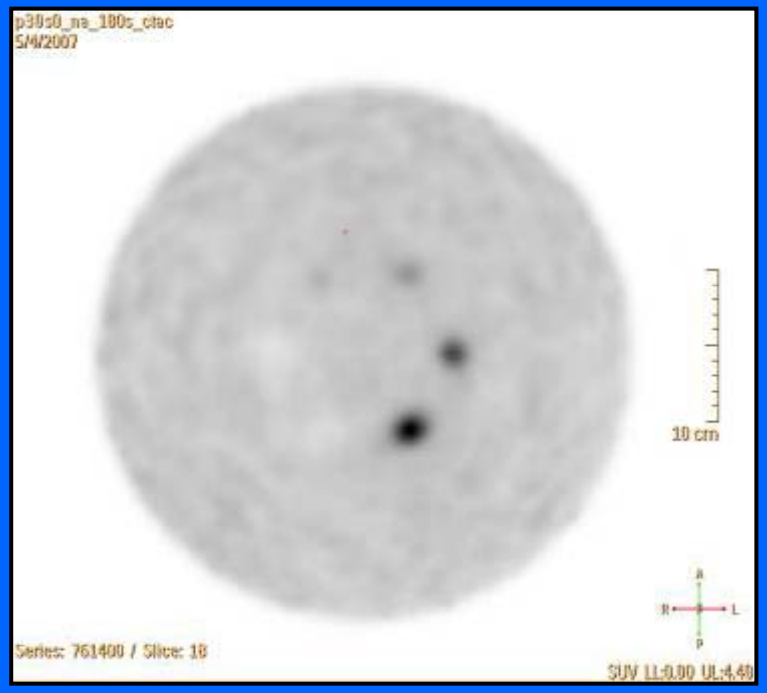



- More counts in same area
- Higher signal-to-noise ratio
- Higher effective NEC/sensitivity

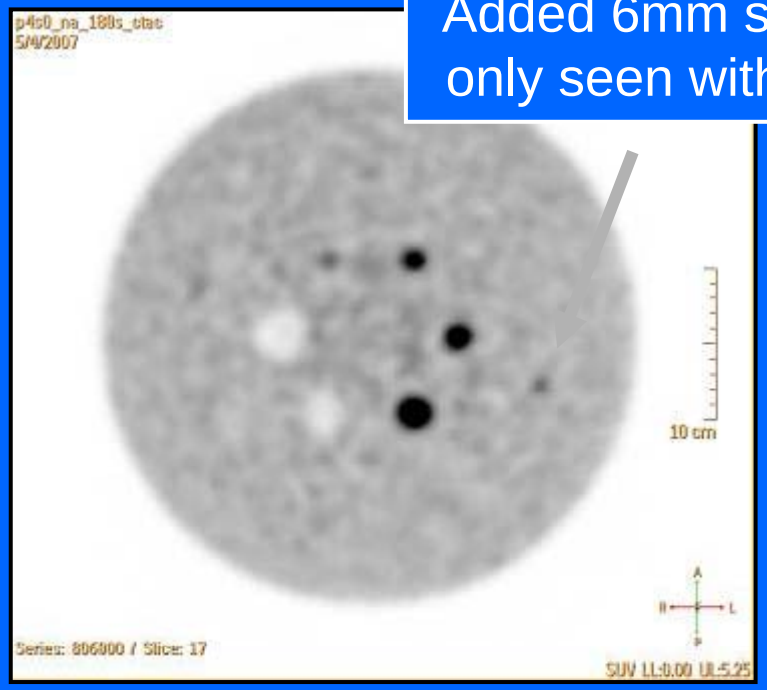
# Impact of Time-of-Flight information

**35 cm Diameter "Big IEC" Phantom (large patient)**
4 mCi, 8:1 hot spheres, 3 min. acquisition time

Non TOF




TOF




Added 6mm sphere only seen with TOF

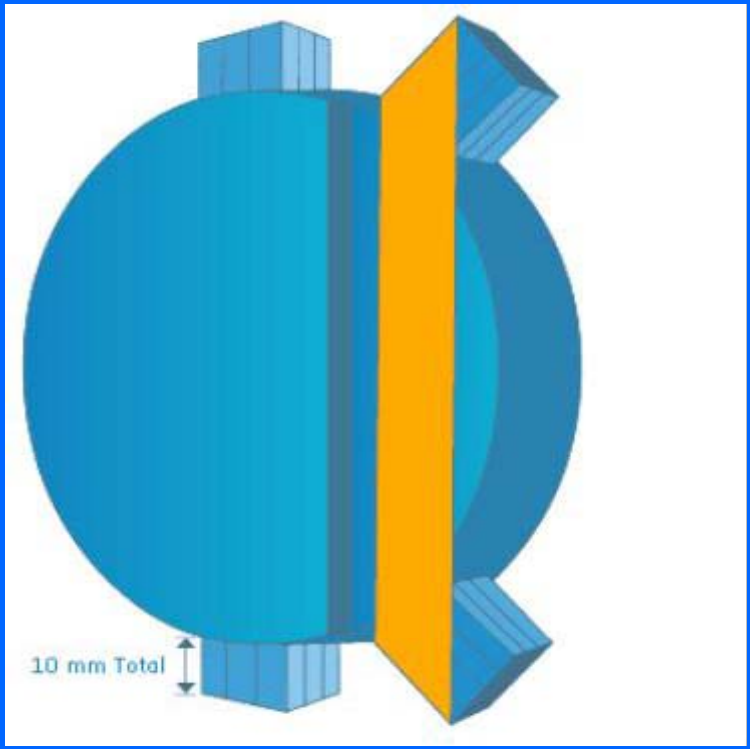
# Future Scintillator Development

Promising scintillators with high light output and fast decay time

| | $LaBr_3$ | $CeBr_3$ | $LuI_3$ |
|---|---|---|---|
| Density | 5.3 | 5.2 | 5.6 |
| Energy Resolution | 3.6 % | 4 % | – |
| Light Yield (rel. LYSO) | ~ 2.1 | ~ 2.1 | ~ 1.6 |
| Decay Time | 20 ns | 17 ns | 25 ns |

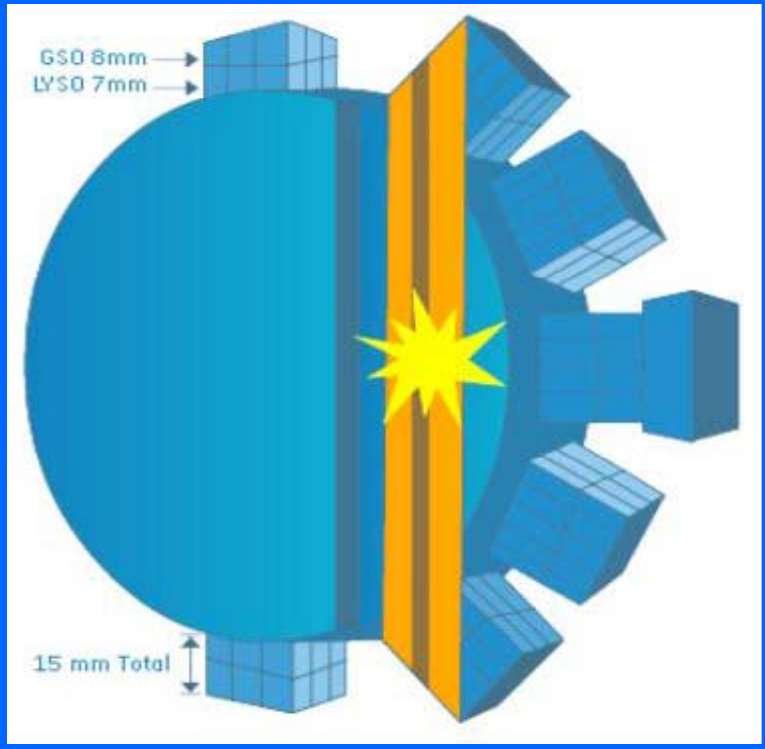
# eXplore Vista & Vista-CT

## Phoswich Detector Modules




- Shorter Crystal = Less Sensitivity
- Small Ring = Less Resolution Uniformity

Small ring diameters magnify parallax effect … critical in determining spatial resolution uniformity




- ✓ **Longer Crystal = Greater Sensitivity**
- ✓ **Small Ring Diameter with Phoswich = Improved Resolution Uniformity**

✓ Depth of Interaction (DOI) = Reduces parallax effect significantly and maintains resolution throughout FOV

# •eXplore Vista & Vista-CT

## •PET Specifications

| | |
|---|---|
| Sensitivity: | 4% @ 250-700 keV |
| | 6.5% @ 100-700 keV |
| Resolution: | < 1 mm w/3D-OSEM |
| | 1.2 mm w/2D-OSEM |
| | 1.45 mm w/FBP |
| Crystal dimensions: | 1.45 mm x 1.45 mm |
| Crystal depth: | 15 mm (8 mm LYSO + 7 mm GSO) |
| Axial FOV: | 47 mm |
| Transaxial FOV: | 68 mm diameter |
| Timing resolution: | 1.5ns |
| Scan geometry: | 3D (w/o septa) |
| Scan Modes: | Static, WB & WB Dynamic, Dynamic, Gated and List Mode |
| Reconstruction Algorithms: | FBP, 2D-OSEM, 3D-OSEM |
| Corrections: | Ge-68 & CT-based attenuation correction, Randoms, Deadtime, Scatter, Decay, Normalization |

imagination at work

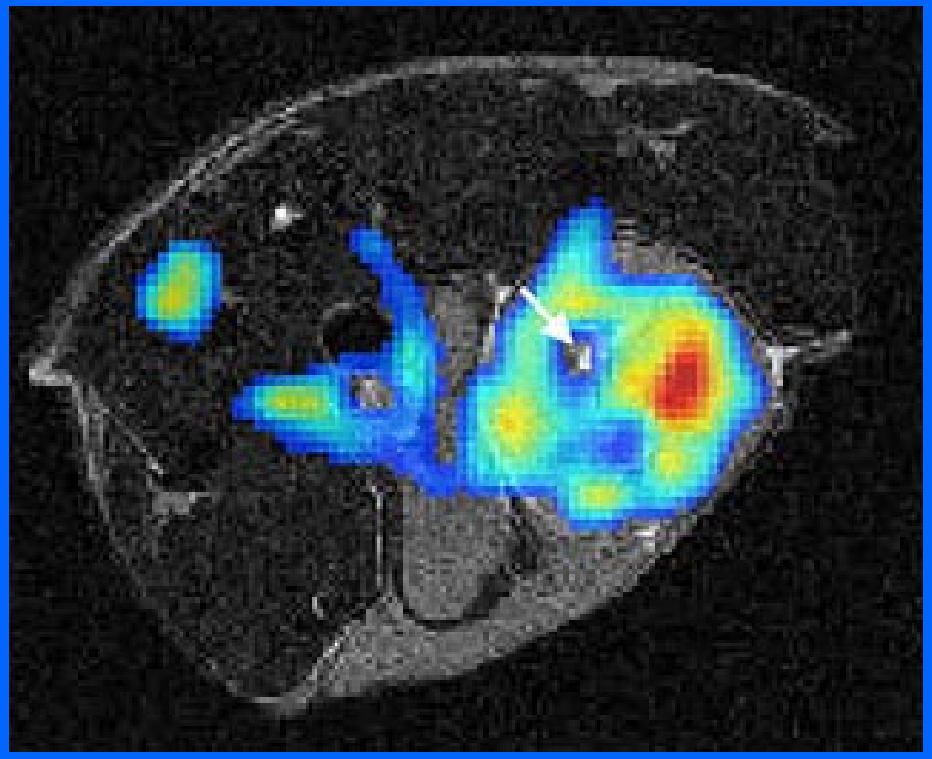
# PET/MR

- PMTs affected by magnetic field
- Fibre optics used to conduct light outside magnet
  - Loss of signal
- Replace PMTs with APDs

# Processing

- Analog processing at detector
- PCB coated by 10μm copper
  - EM shielding
  - Thin enough for no eddy currents

# PET/MR tumour image



Cherry et al., UC Davis

# Megavoltage Imaging

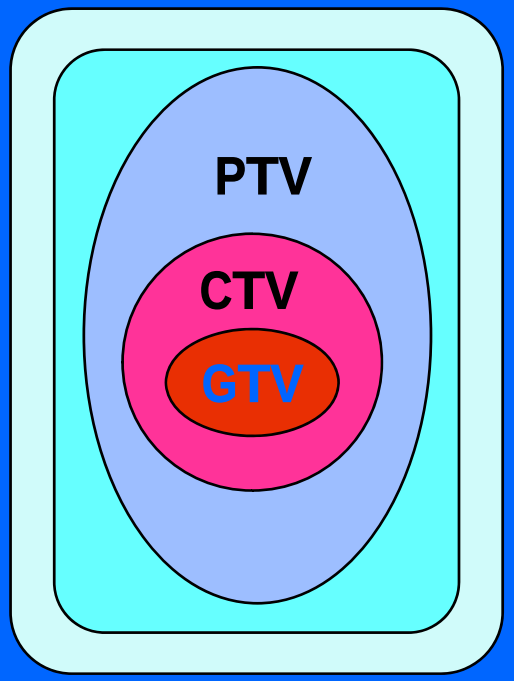
- Photon energy 4-25MeV

# Target Volumes

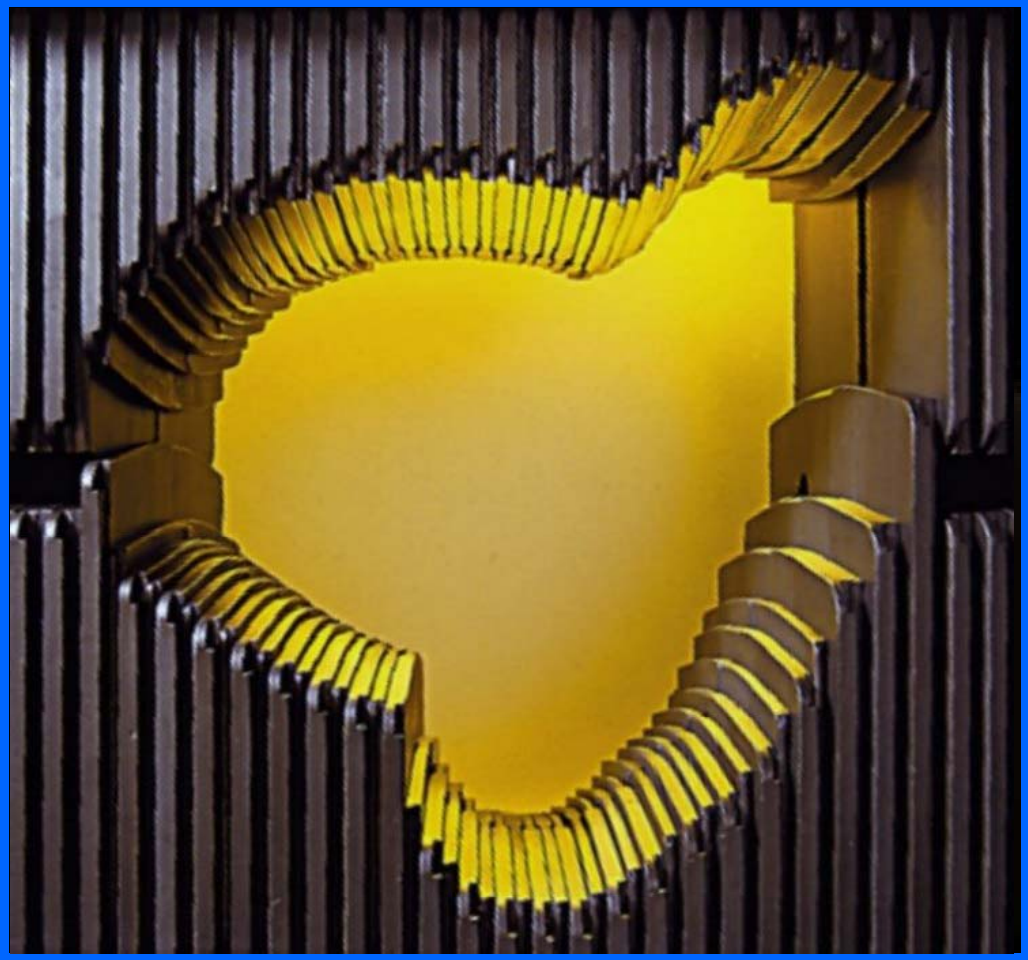
- GTV - Gross Target Volume
  includes tumor that can be seen in treatment planning images (typically CT, MR or PET).

- CTV - Clinical Target Volume
  includes the GTV plus regional lymph nodes and tissue adjacent to the GTV that may contain microscopic tumor cells.
  The CTV is what the physician wants to treat.

- PTV - Planning Target Volume
  includes CTV plus a margin of healthy tissue to account for inter- and intrafraction organ motion.
  In order to treat the CTV, the planner must design a treatment plan for the PTV.



# MLC Beam Delivery

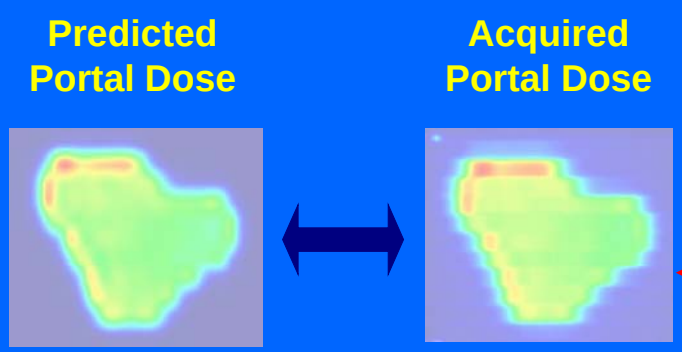


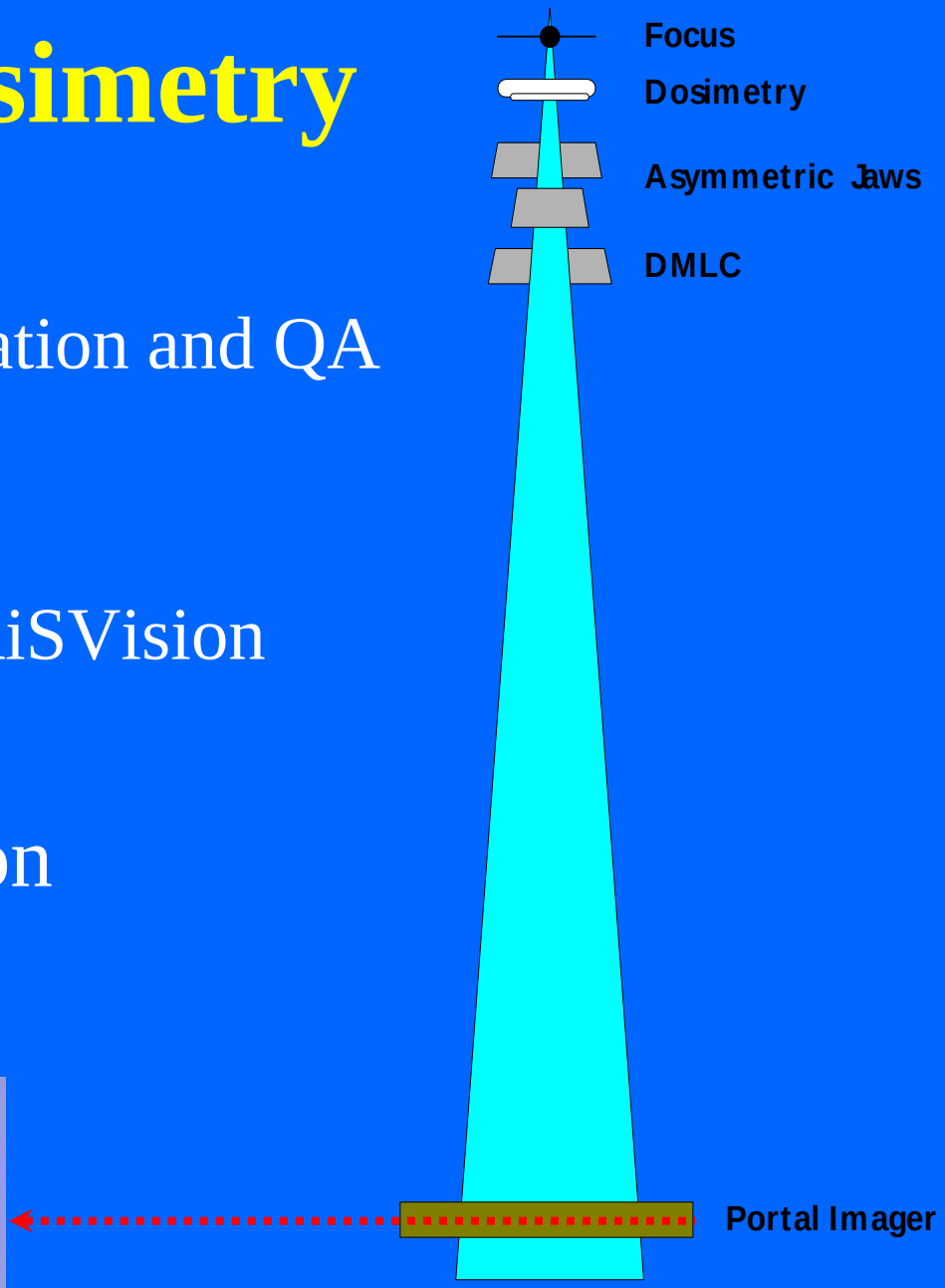
Key C-Series® Technology:

- 120 leaf high resolution MLC
- Dual redundant safety readout

# PortalVision Dosimetry

- Application
  - Pre-Treatment Verification and QA
    - Line Profile
    - Gamma Analysis
  - Results Stored in VARiSVision with the Treatment Plan
- Qualitative Comparison

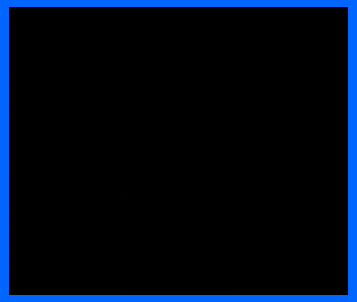


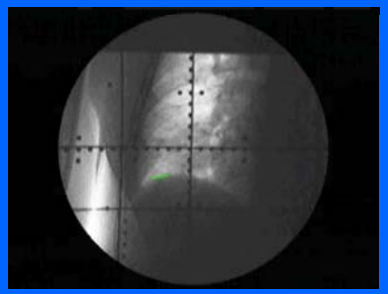



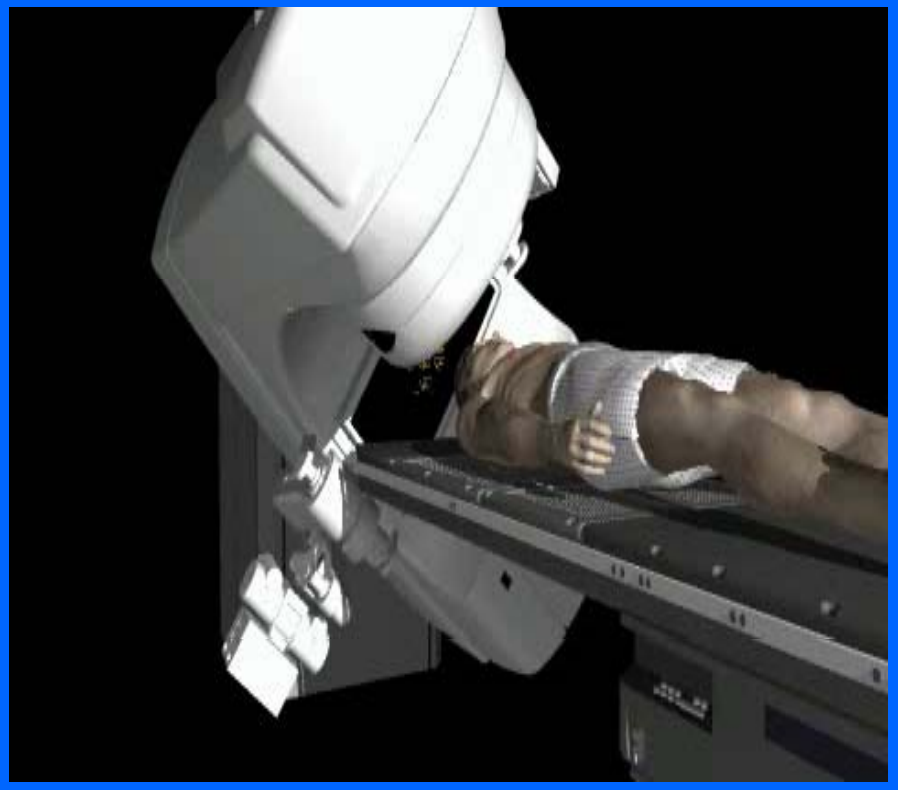

FDA 510(k)

# Dynamic Targeting with On Board Imaging

- What data can we acquire ?
  - Single Shot KV and MV
  - Cone Beam CT
  - Real Time Flouro
  - Related KV and MV Images





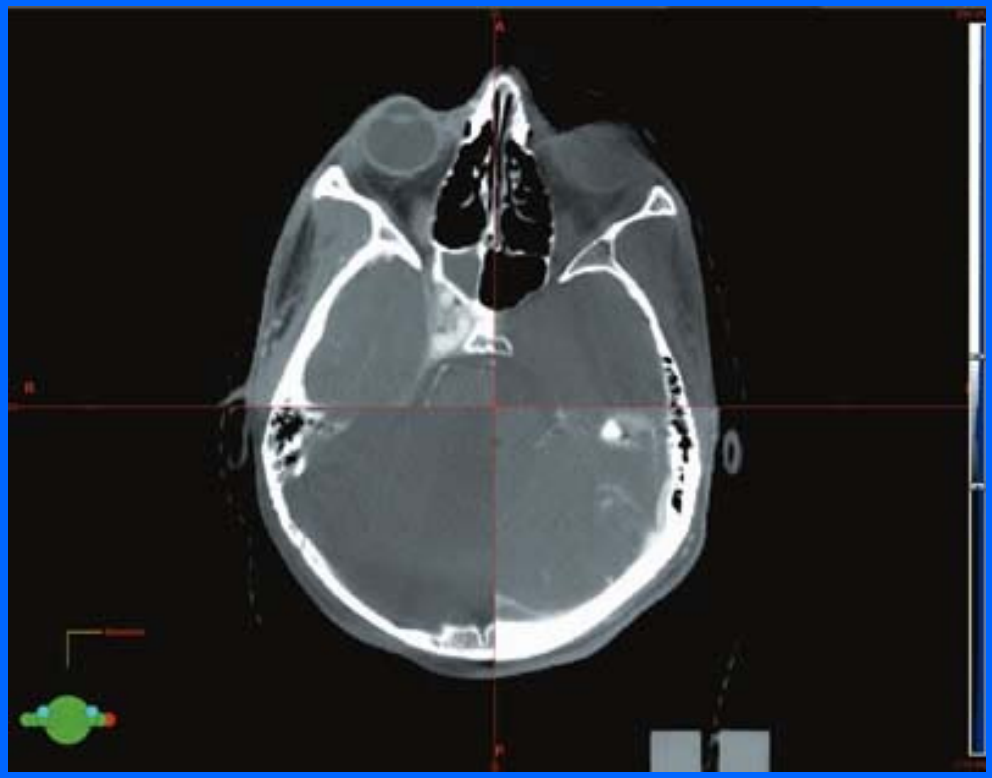



CLINAC
CAUTION

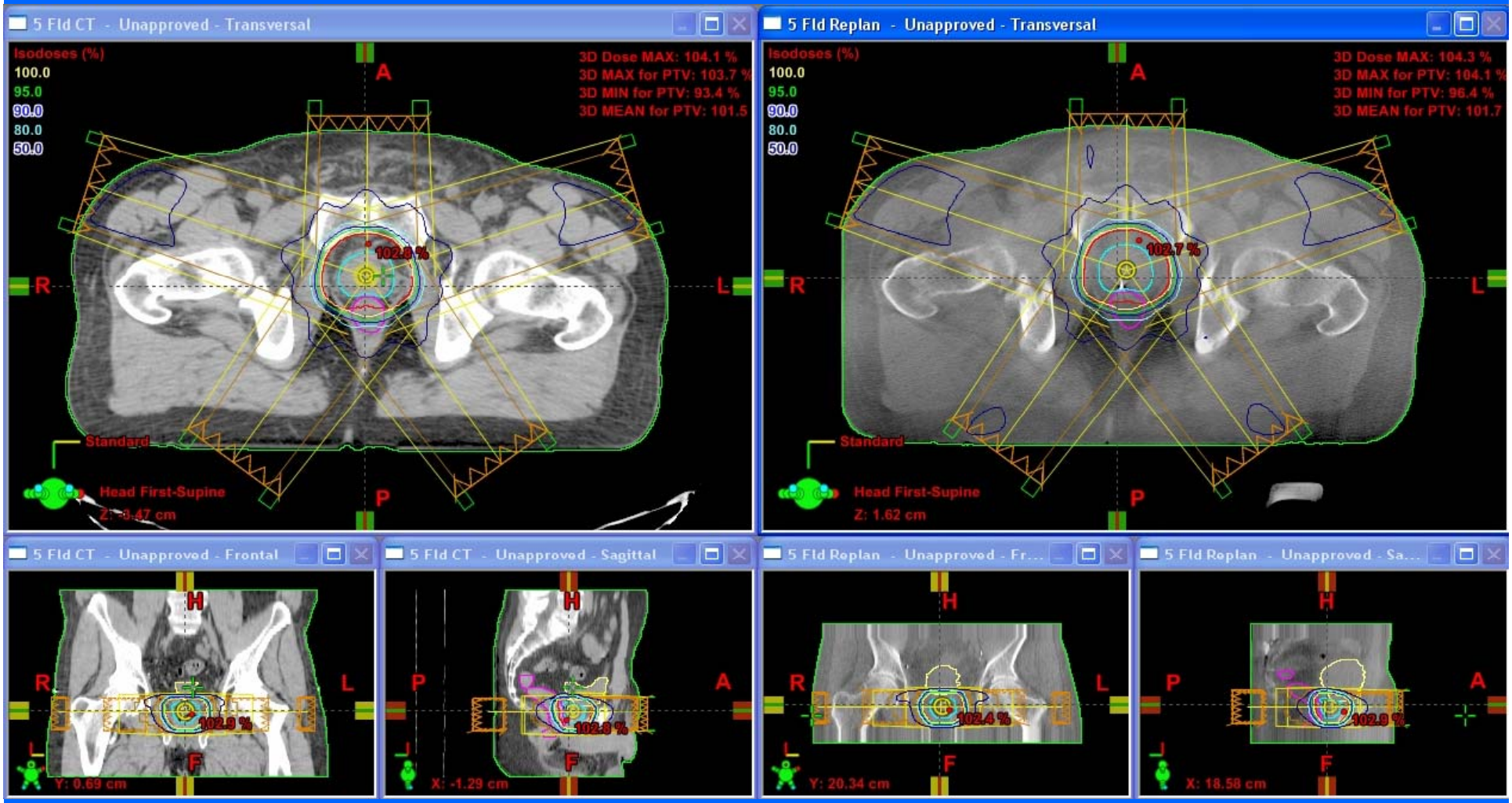
# IGRT System

X-ray Source - Varian G242 X-ray tube; 40 to 125 kVp
Imaging Panel - Varian PaxScan 4030a, a-Si
2048 x 1536 pixel resolution
up to 15 fps
Robotic Arms - 3 pivot points: similar to shoulder, elbow and wrist
completely retractable
Infrared pendant - controls all three arms
(PortalVision and On-Board Imager)
Dedicated Control Console - remote motion of all three arms from the control console
Remote Couch Motion

# Fused kV and CBCT image



# CBCT Re-plan


5 Fld CT - Unapproved - Transversal
Isodoses (%)
100.0
95.0
90.0
80.0
50.0
3D Dose MAX: 104.1 %
3D MAX for PTV: 103.7 %
3D MIN for PTV: 93.4 %
3D MEAN for PTV: 101.5
102.8 %
Standard
Head First-Supine
5 Fld Replan - Unapproved - Transversal
3D Dose MAX: 104.3 %
3D MAX for PTV: 104.1 %
3D MIN for PTV: 96.4 %
3D MEAN for PTV: 101.7
102.7 %
Z: 1.62 cm
5 Fld CT - Unapproved - Frontal
Y: 0.69 cm
5 Fld CT - Unapproved - Sagittal
X: -1.29 cm
5 Fld Replan - Unapproved - Fr...
102.4 %
Y: 20.34 cm
5 Fld Replan - Unapproved - Sa...
X: 18.58 cm

# Acknowledgements


- Colleagues in NHSGGC
- GE
- Philips
- Siemens
- Varian

# Medical Applications of Position Sensitive Detectors

Alex Elliott

Dept of Clinical Physics

University of Glasgow