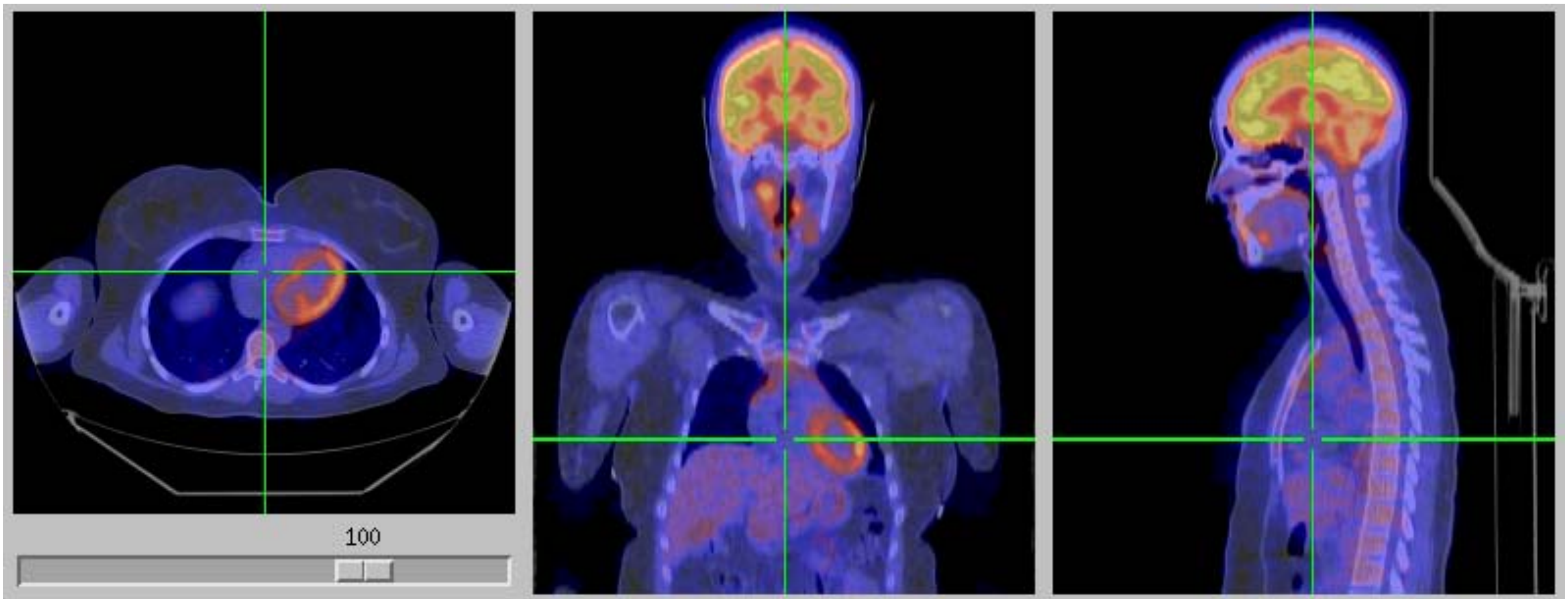
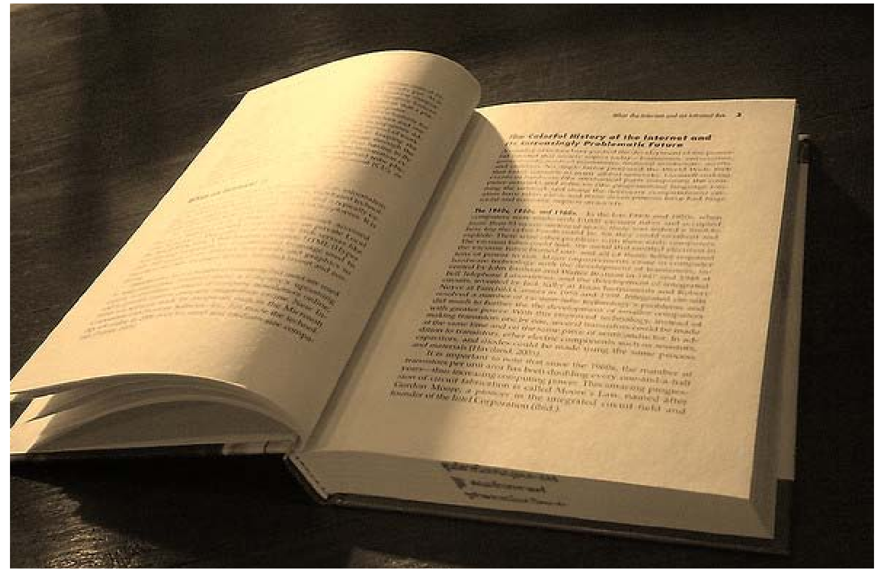
Multimodality PET/CT Imaging



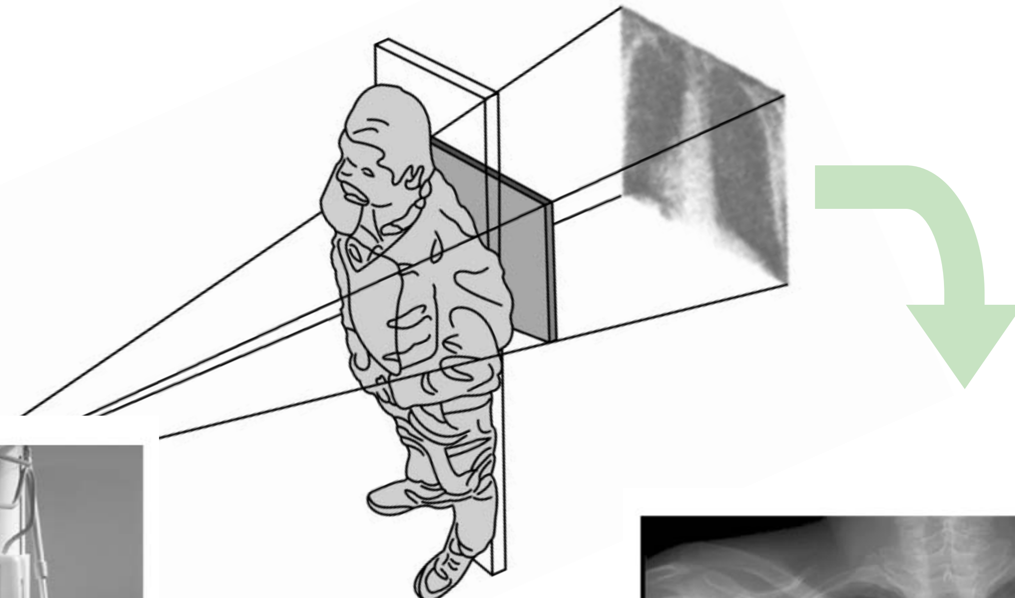
Paul Kinahan
Imaging Research Laboratory
Director, PET/CT Physics
Department of Radiology

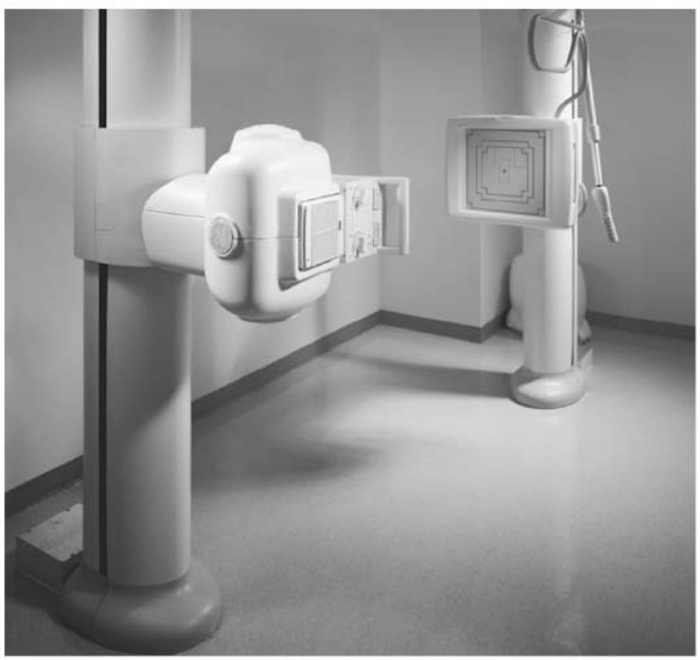
Types of Images



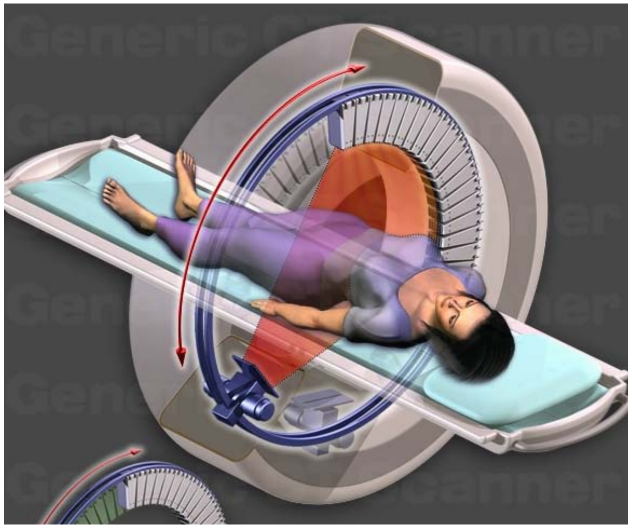
René Magritte *The Treachery of Images* 1928

Types of Images: Projection Imaging

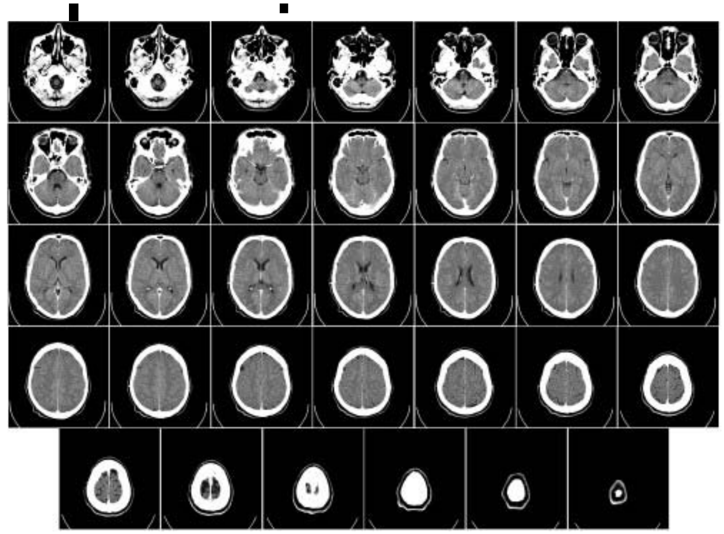




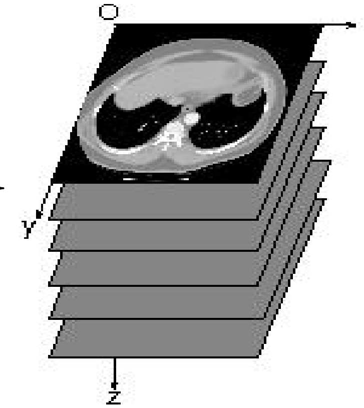
Types of Images: Tomography



tomographic acquisition



reconstruction of multiple images



form image volume

image processing

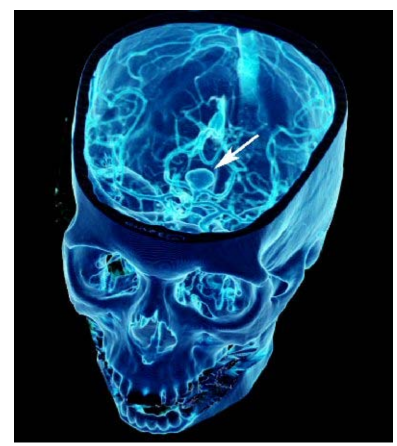
simple

transaxial or axial view

coronal view

sagittal view

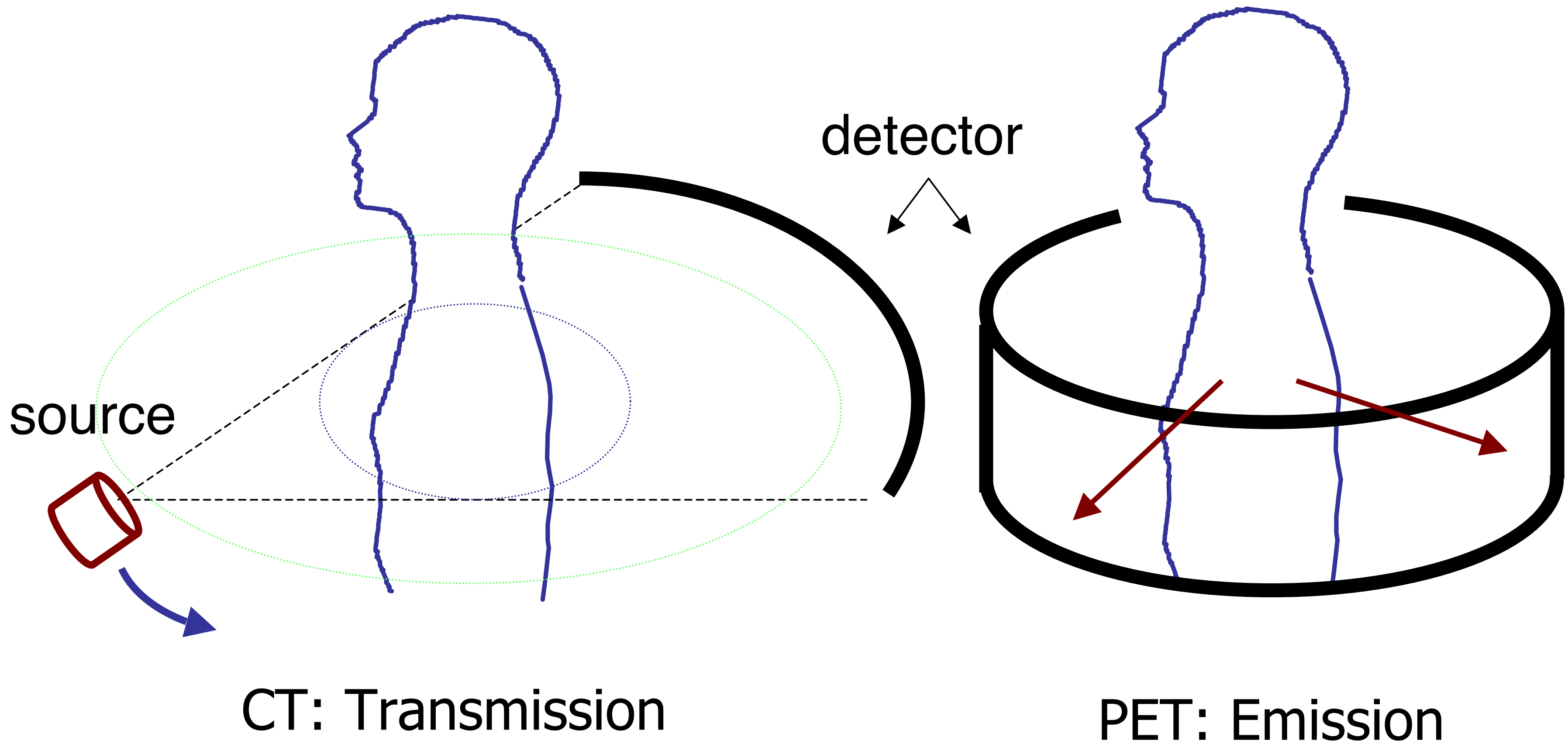
sophisticated



basilar tip aneurysm

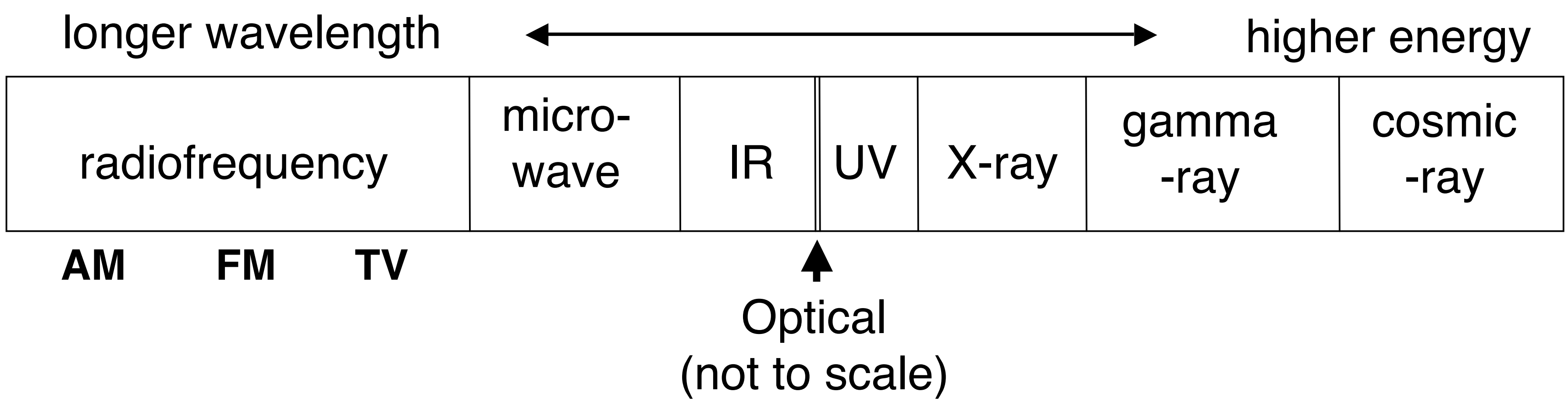
Two Types of Tomography

'Tomo' + 'graphy' = Greek: 'slice' + 'picture'

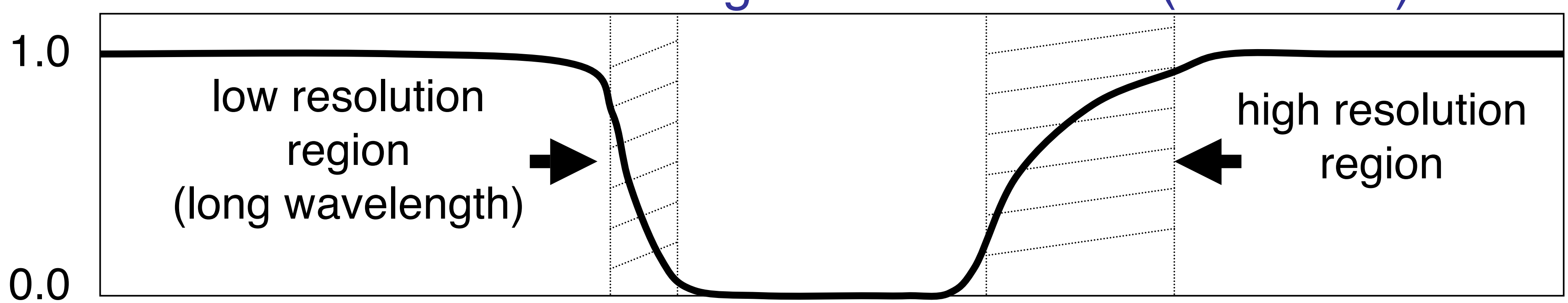


Physics of PET and CT Imaging

The Electromagnetic Spectrum



Transmission through 10cm of tissue (i.e. water)

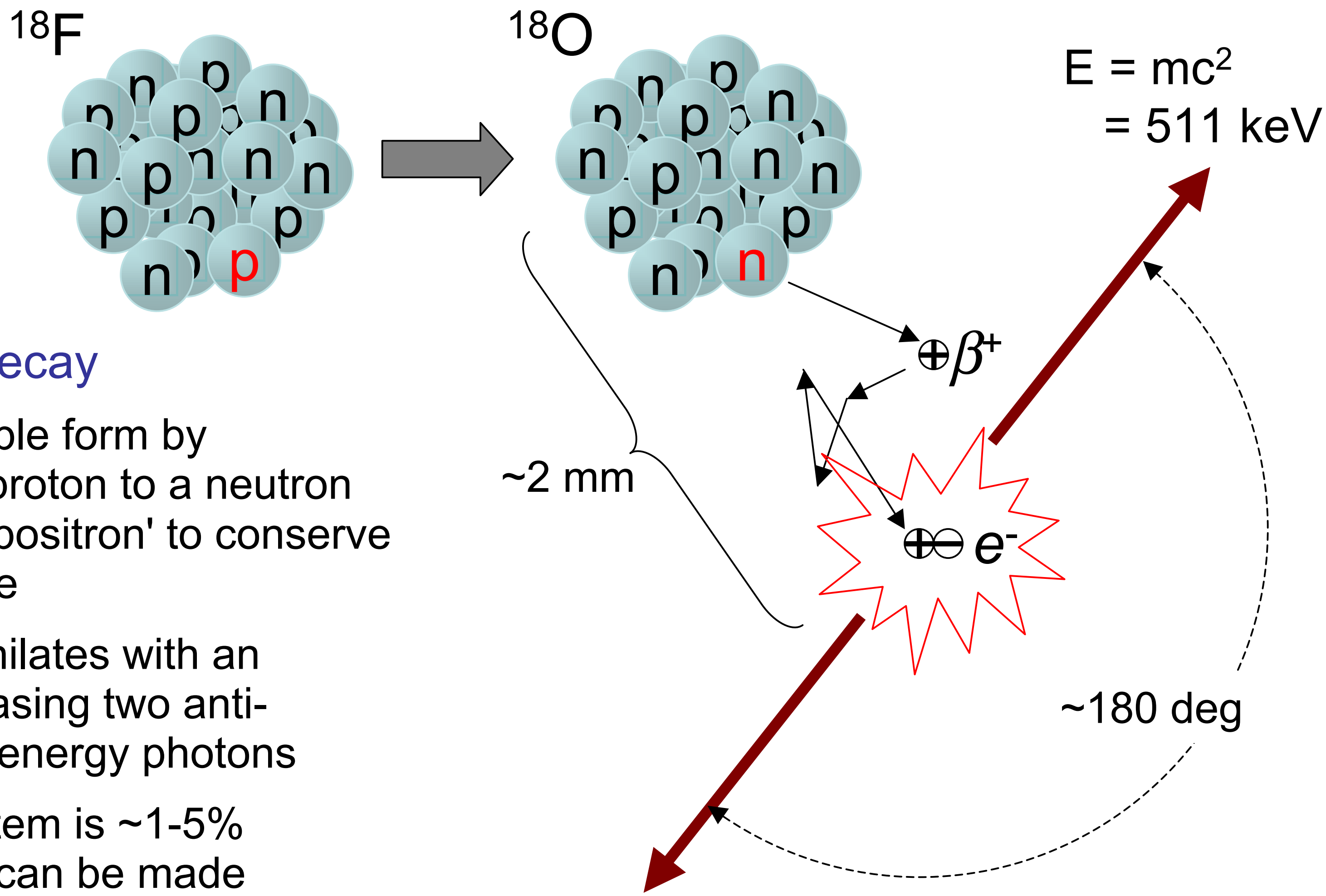


Major Medical Imaging Modalities

Modality	Resolution (mm)	TX or EM*	Mode
X-ray	0.1 – 1.0	TX	Projection
Nuclear Medicine	10 – 20	EM	Projection
X-ray CT	0.5	TX	Tomographic
Ultrasound	0.3	TX (sound)	Tomographic
MRI	1	EM (RF)	Tomographic
SPECT	10	EM	Tomographic
PET	5	EM	Tomographic

*(TX = transmission, EM = emission)

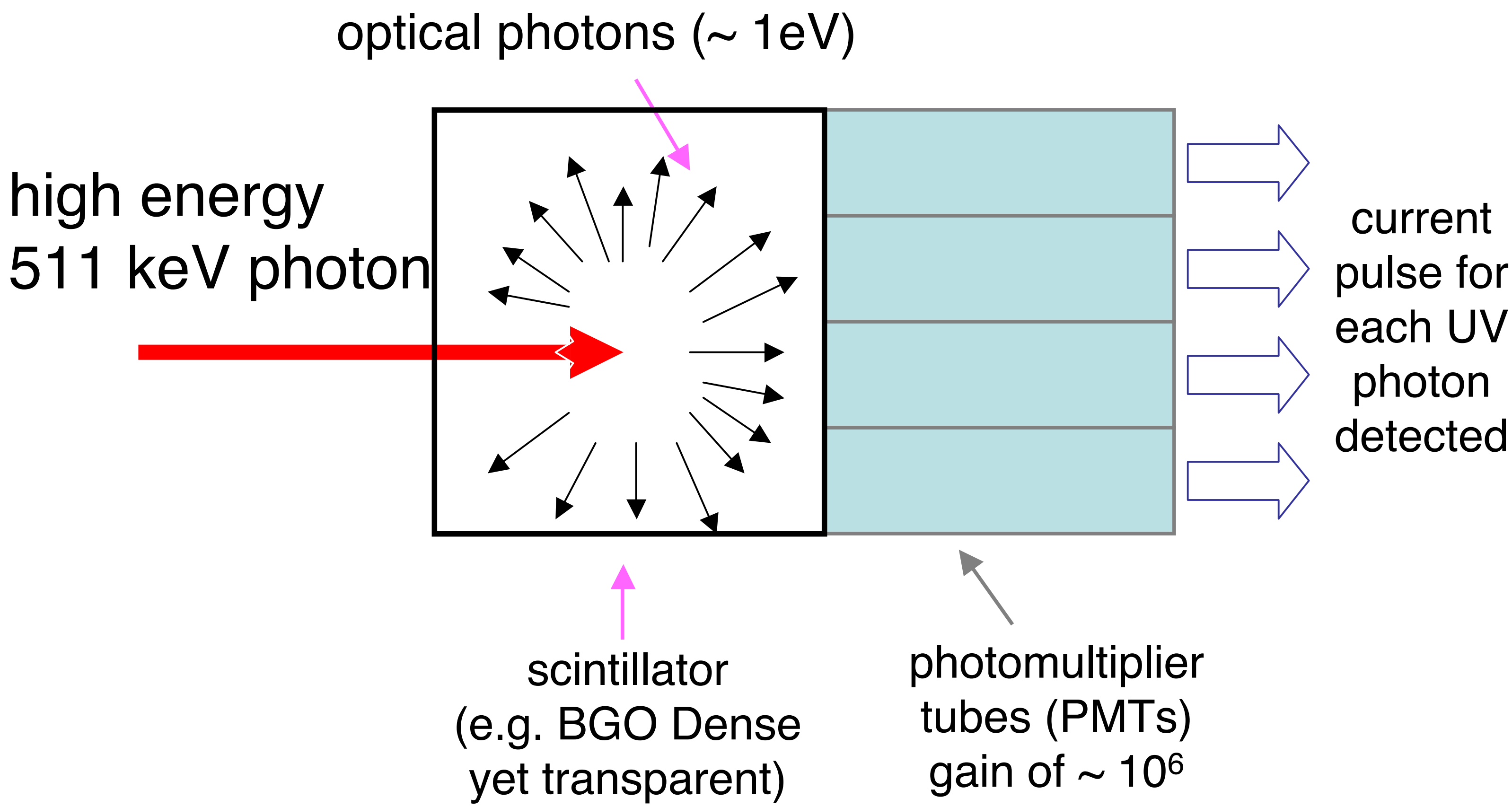
How it works: Positron Emission



Radioactive decay

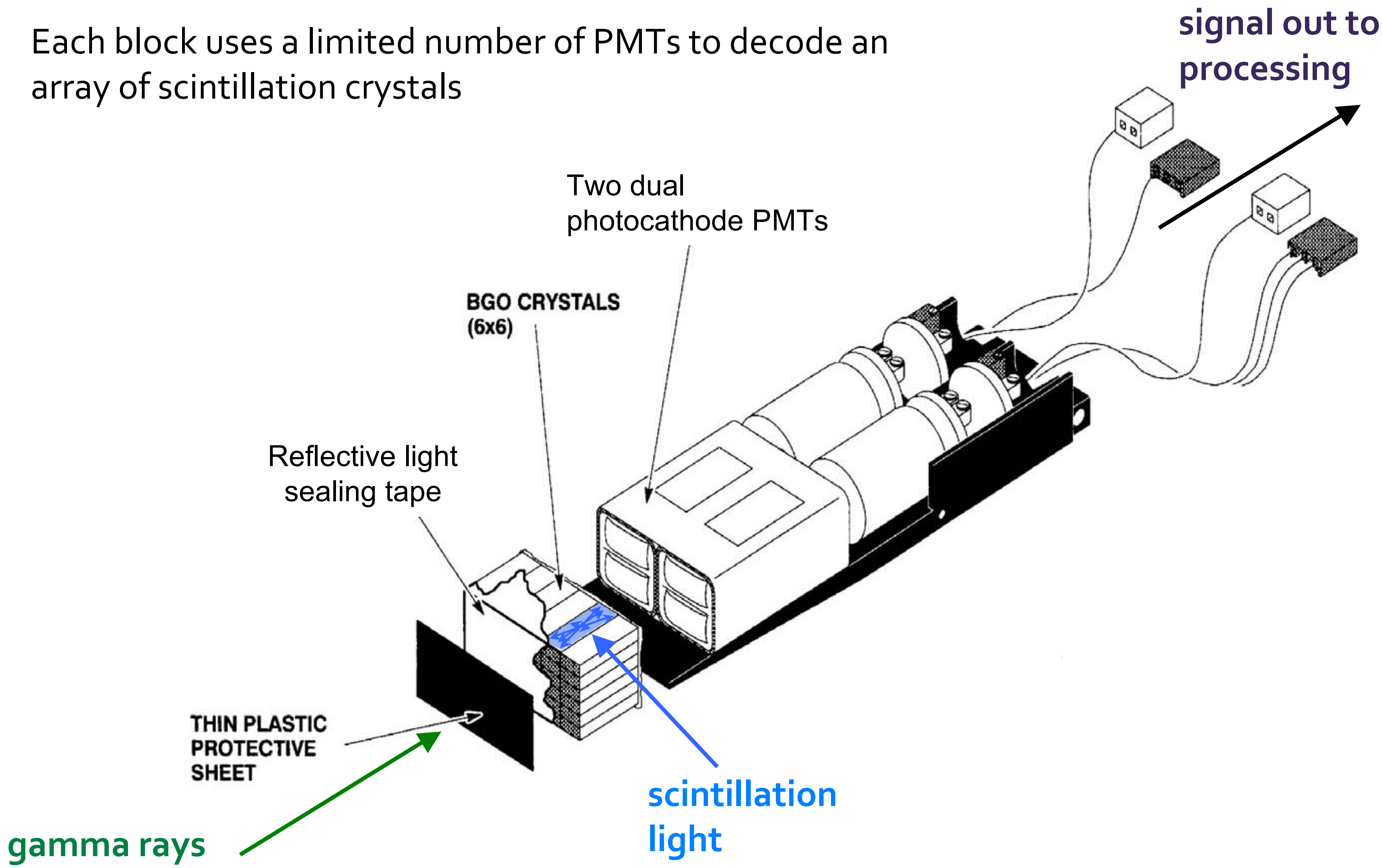
- decays to stable form by converting a proton to a neutron and ejects a 'positron' to conserve electric charge
- positron annihilates with an electron, releasing two anti-colinear high-energy photons
- detection system is ~1-5% efficient, and can be made quantitative

How it works: Scintillation

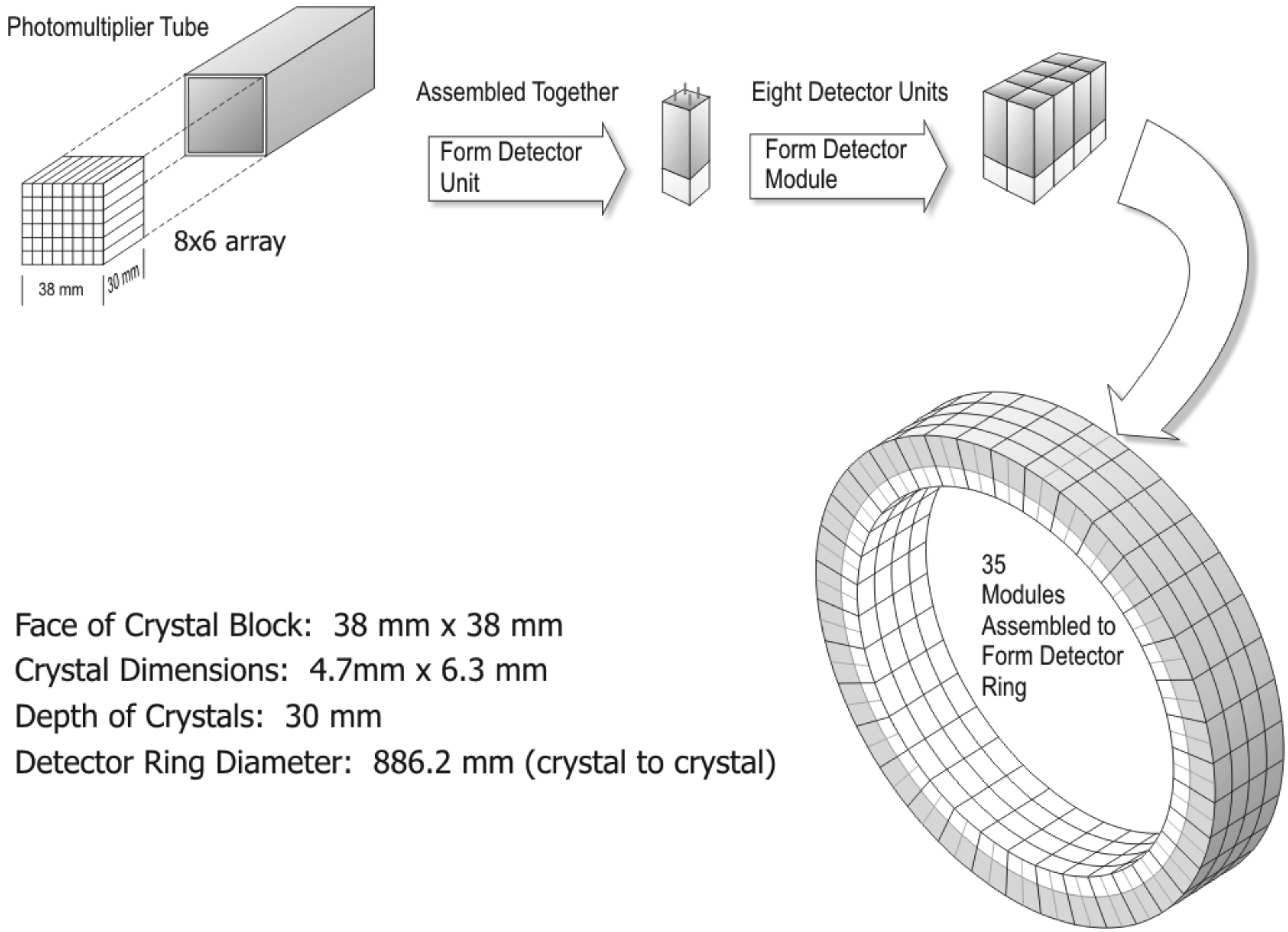


PET Detector Block

- PET scanners are assembled in block modules
- Each block uses a limited number of PMTs to decode an array of scintillation crystals



Typical PET Scanner Detector Ring



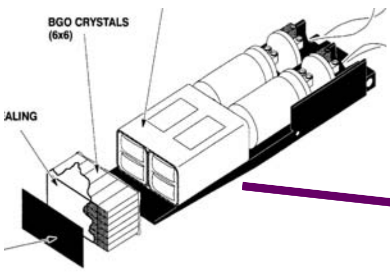
Face of Crystal Block: 38 mm x 38 mm

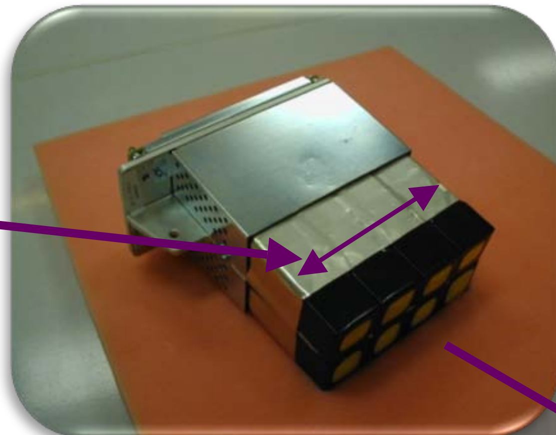
Crystal Dimensions: 4.7mm x 6.3 mm

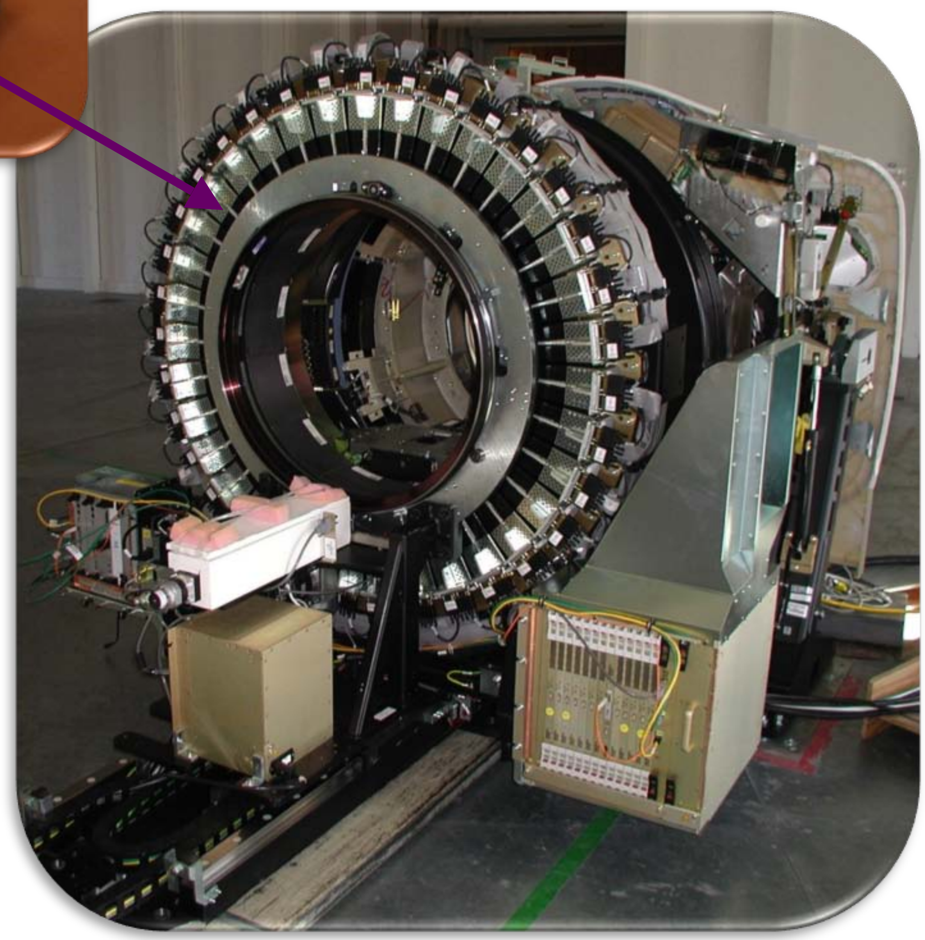
Depth of Crystals: 30 mm

Detector Ring Diameter: 886.2 mm (crystal to crystal)

Inside GE Discovery STE PET/CT







<u>Block matrix: BGO crystals</u>

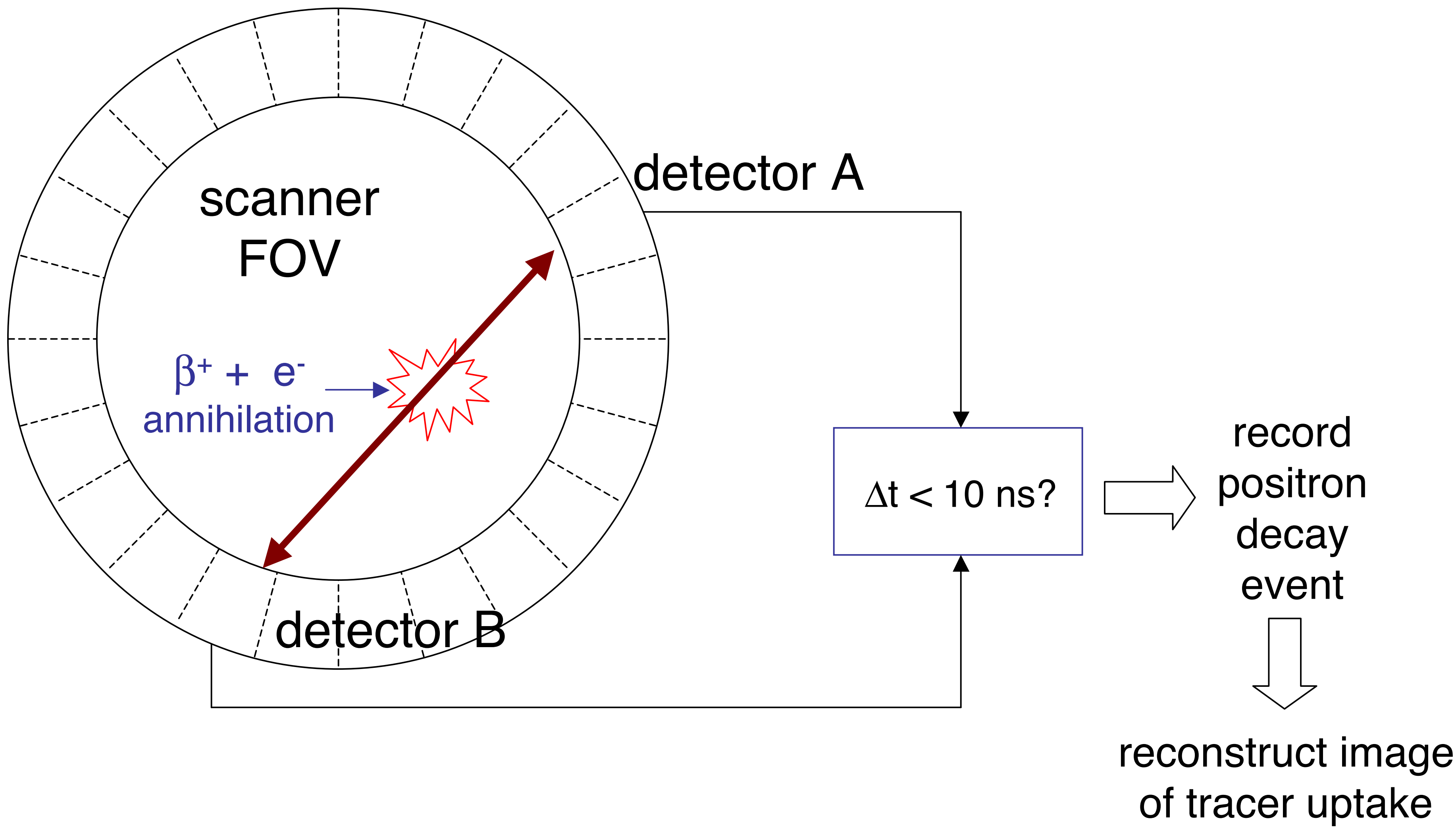
- 6 x 8 crystals (axial by transaxial)
- Each crystal:
  - 6.3 mm axial
  - 4.7 mm transaxial

<u>Scanner construction</u>

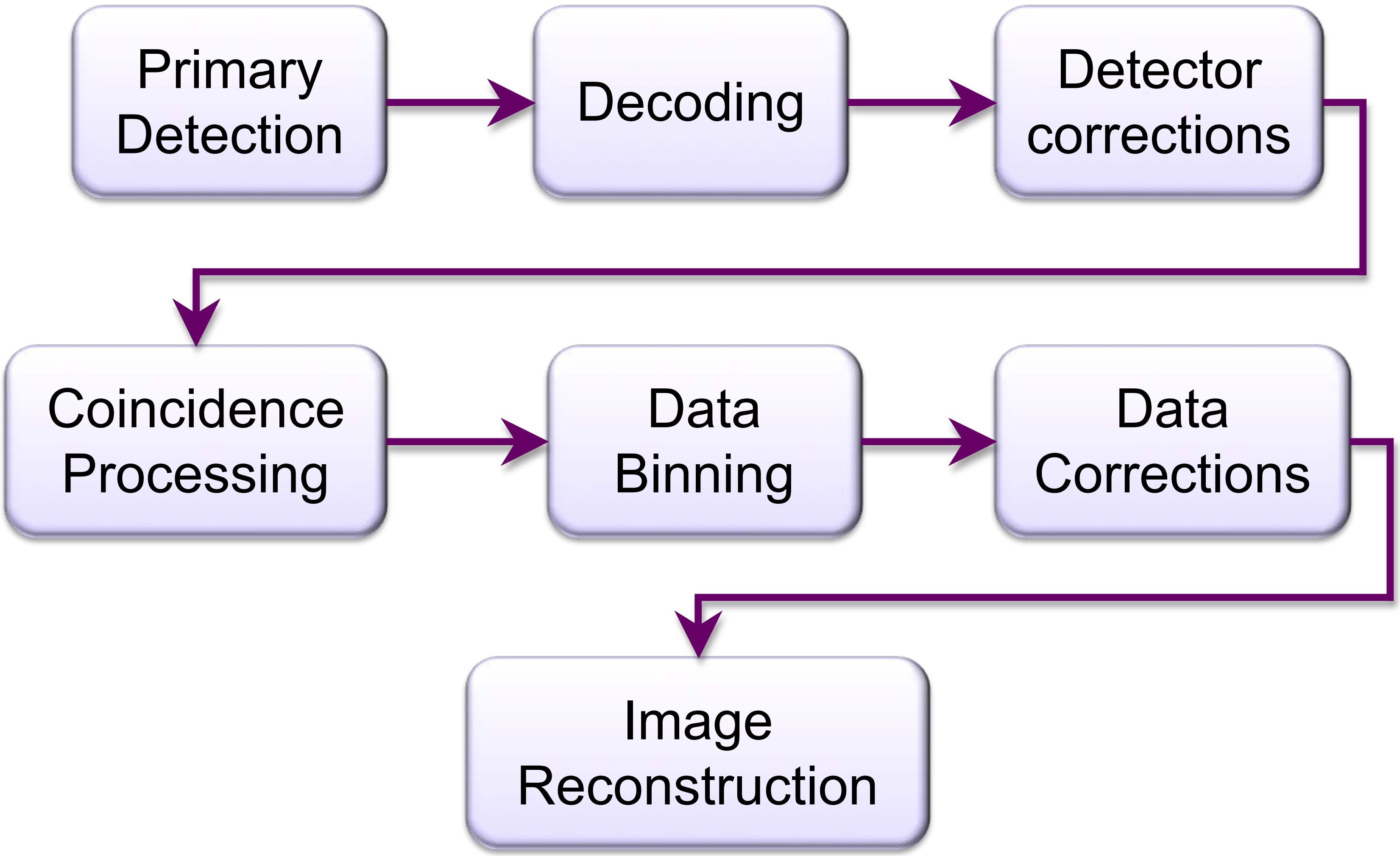
- Axial:
  - 4 blocks axially = 24 rings
  - 15.7 cm axial extent
- Transaxial:
  - 70 blocks around = 560 crystals
  - 88 cm BGO ring diameter
  - 70 cm patient port

13,440 individual crystals

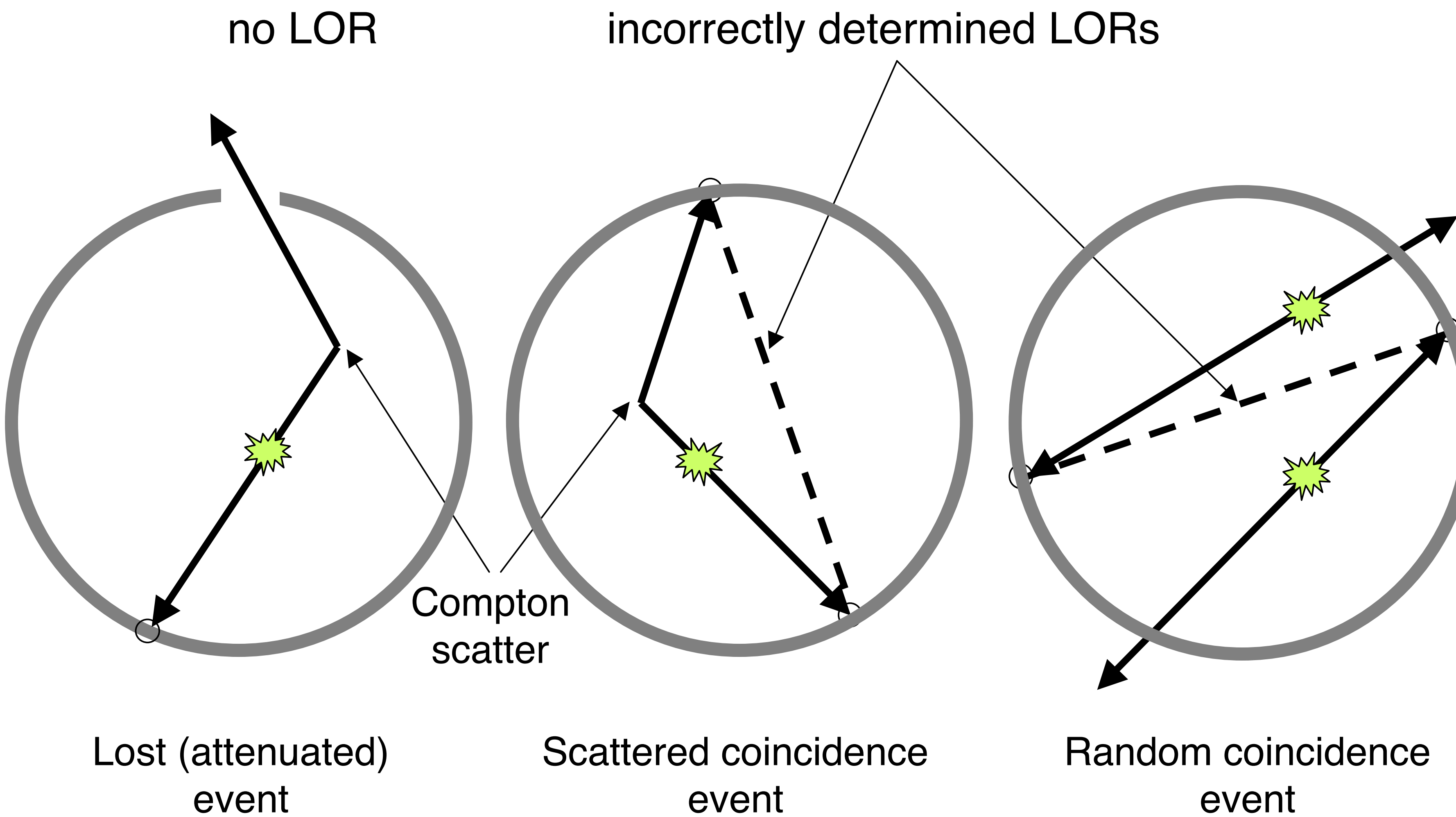
How it works: Timing coincidence



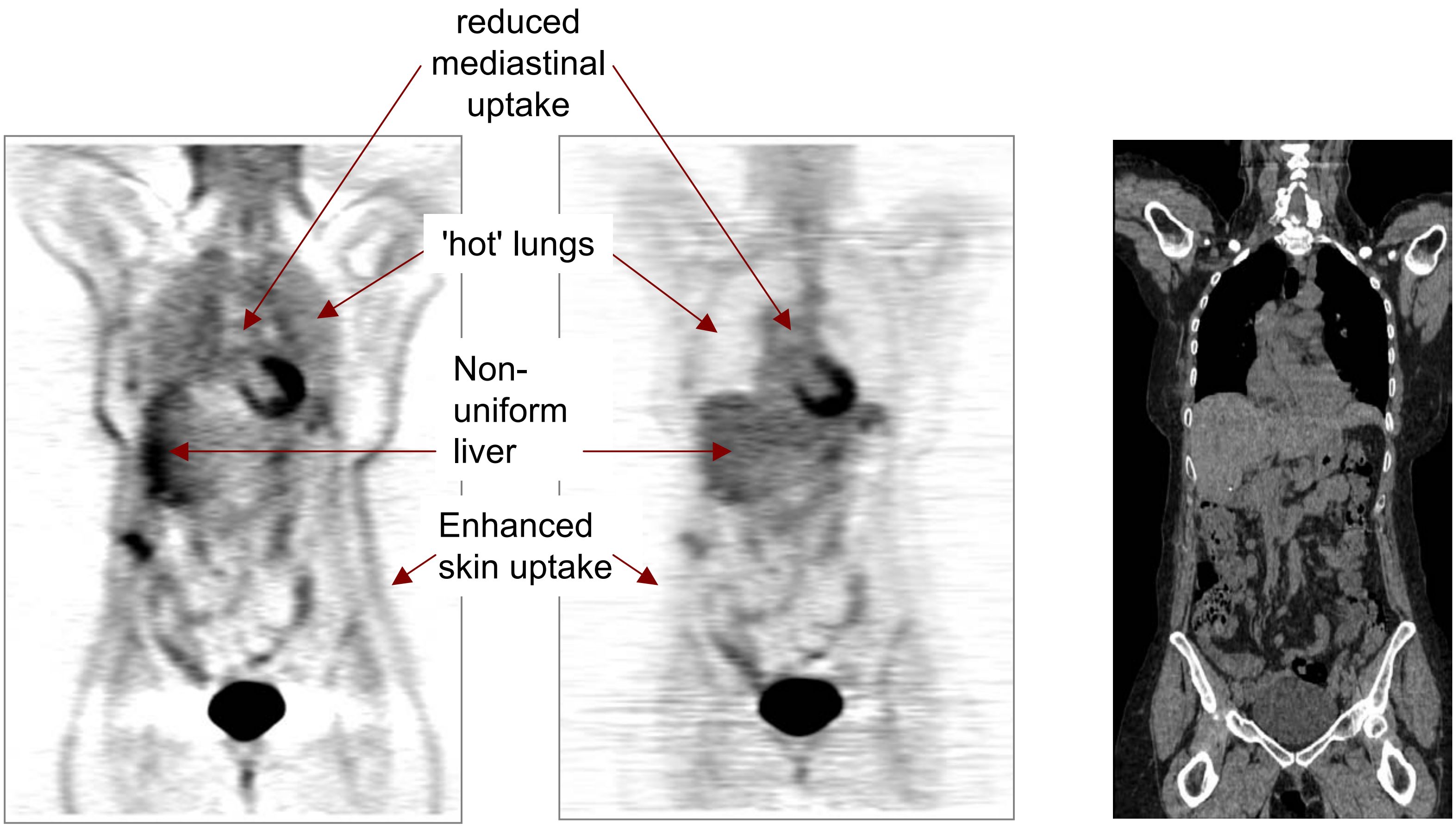
PET Image Formation Workflow



Quantitative errors in measurement



Effects of Attenuation: Patient Study



PET: without attenuation correction

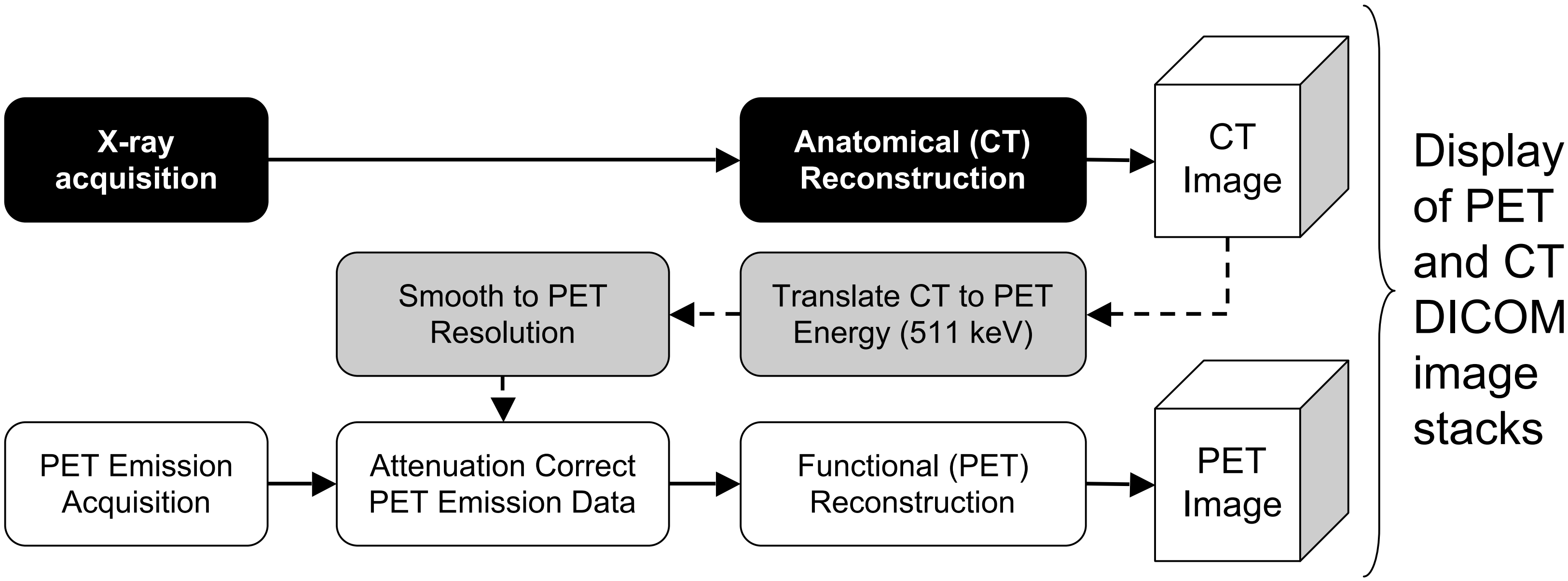
PET: with attenuation correction (accurate)

CT image (accurate)

Errors in attenuation correction can dominate image quality

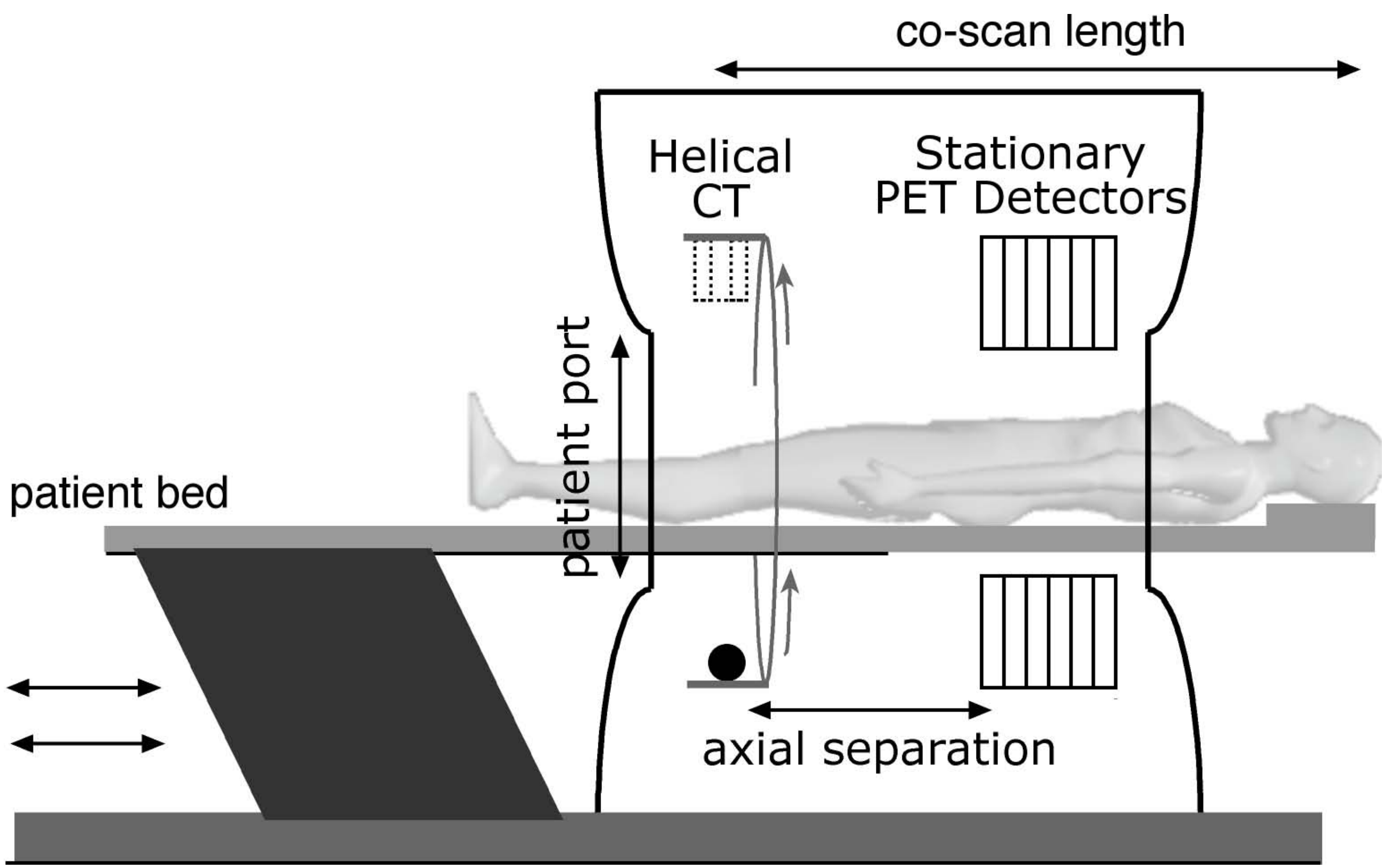
PET/CT Scanner Physiology

- CT images are also used for attenuation correction (CTAC) of the PET data



- Note that images are not really fused, but are displayed as fused or side-by-side with linked cursors

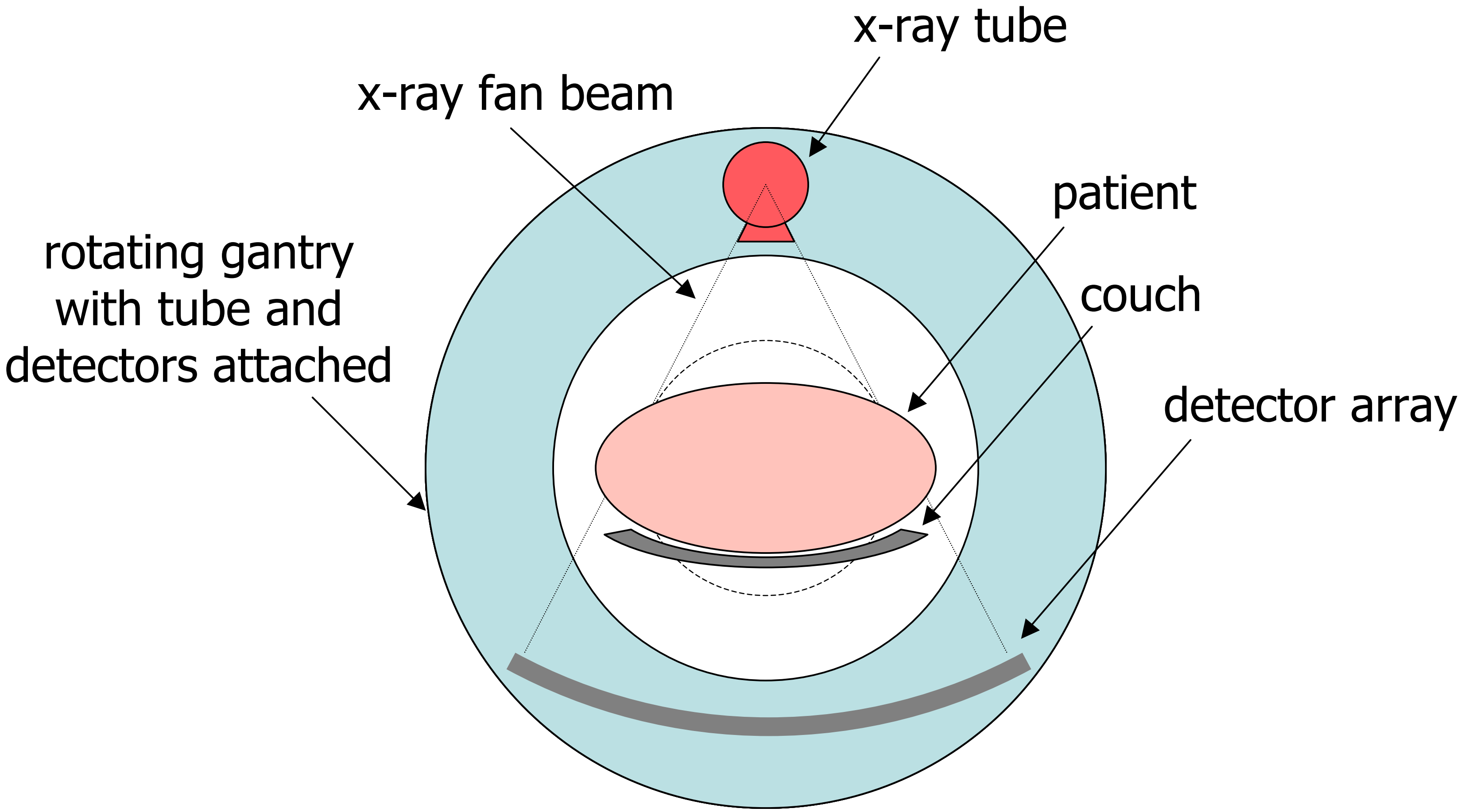
Basic PET/CT Architecture



Commercial/Clinical PET/CT Scanner

rotating CT system | thermal barrier | PET detector blocks

How it works: CT Scan Concept

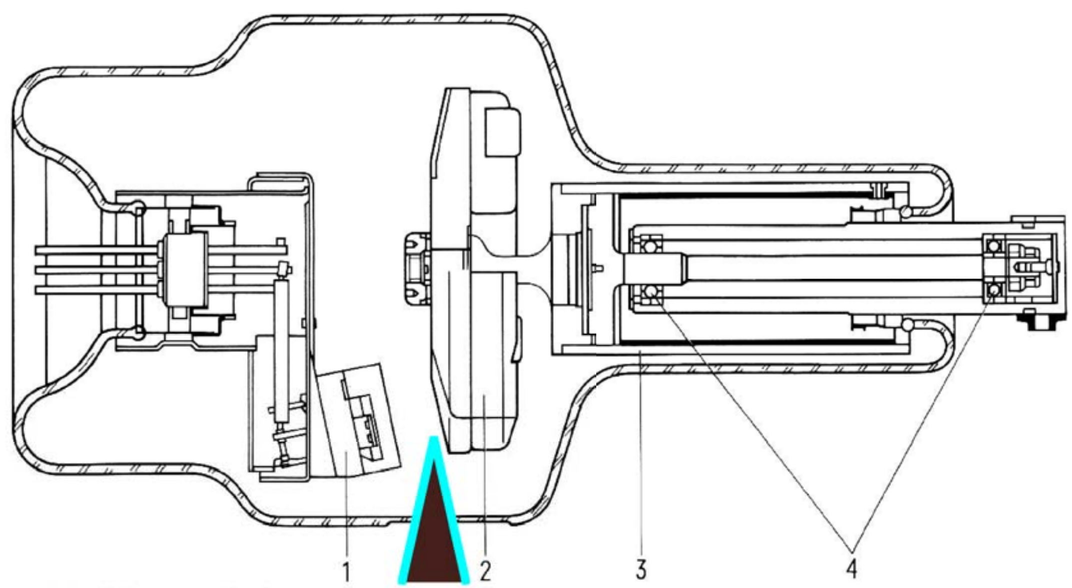


CT Scanner in Operation

64-slice CT, weight ~ 1 ton, speed 0.33 sec (180 rpm)

X-ray CT Tubes

- Rotating anode tube
  (dissipates heat to allow higher beam currents)

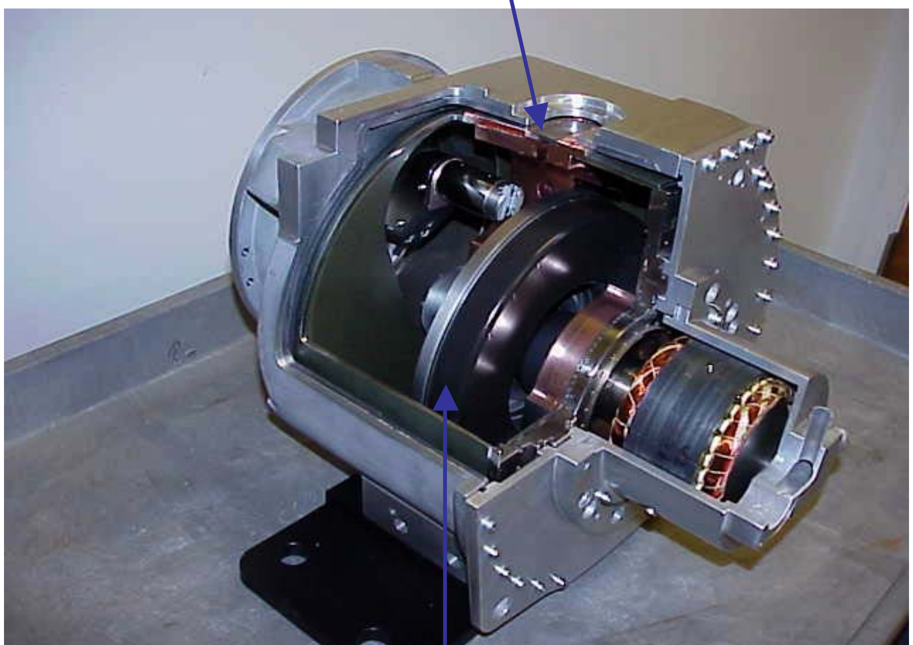


1 Dual focus cathode
2 Graphite-RTM compound anode
3 Rotor
4 Ball bearings

Fig. 7.17 Cross-section through a rotating anode x-ray tube

Modern X-Ray Tube

Electron Collector: reduce off-focal radiation
- Lower patient dose



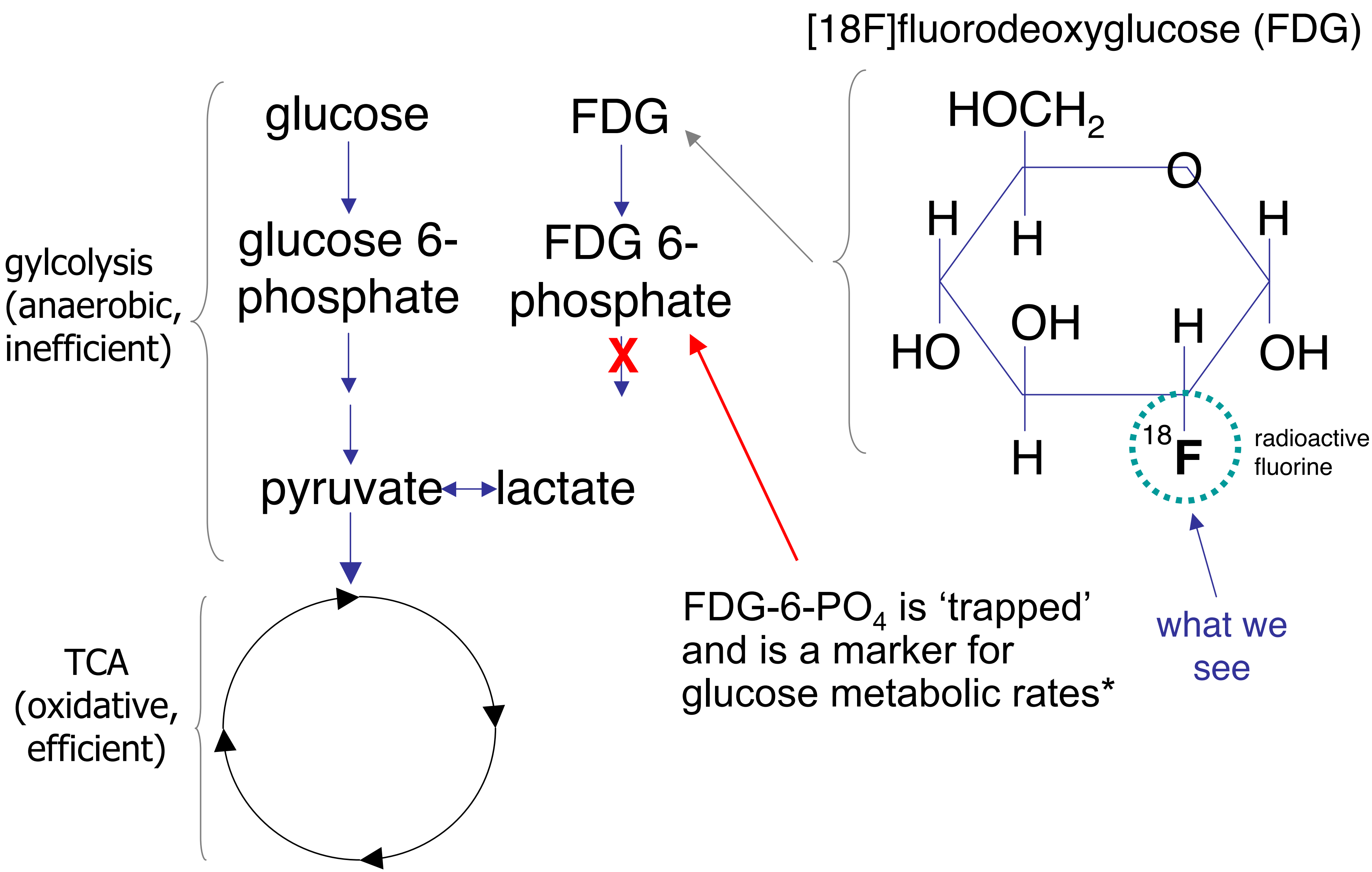
High Peak-Power Target & Bearings
- High peak-mA for fast rotation

Rotation speed (s)	typical mAs	mA neede d	
0.5	200	400	
0.4	200	500	Large Patient
0.4	240	600	
0.35	200	571	Large Patient
0.35	240	686	

kVp	mA Small Spot	mA Large Spot
80	10-300	305-675
100	10-310	315-770
120	10-335	340-800
140	10-335	340-715

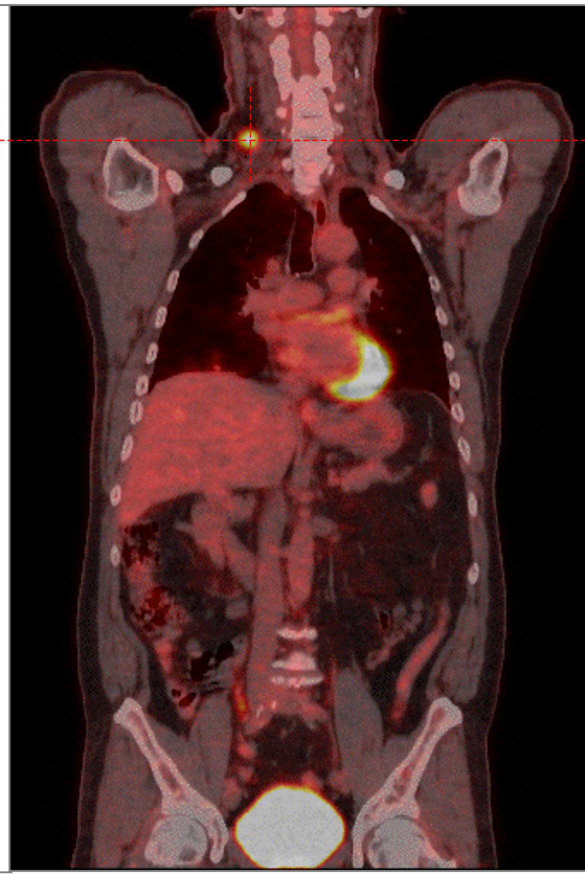
What are we looking at?

Molecular Imaging: Glu Metabolism

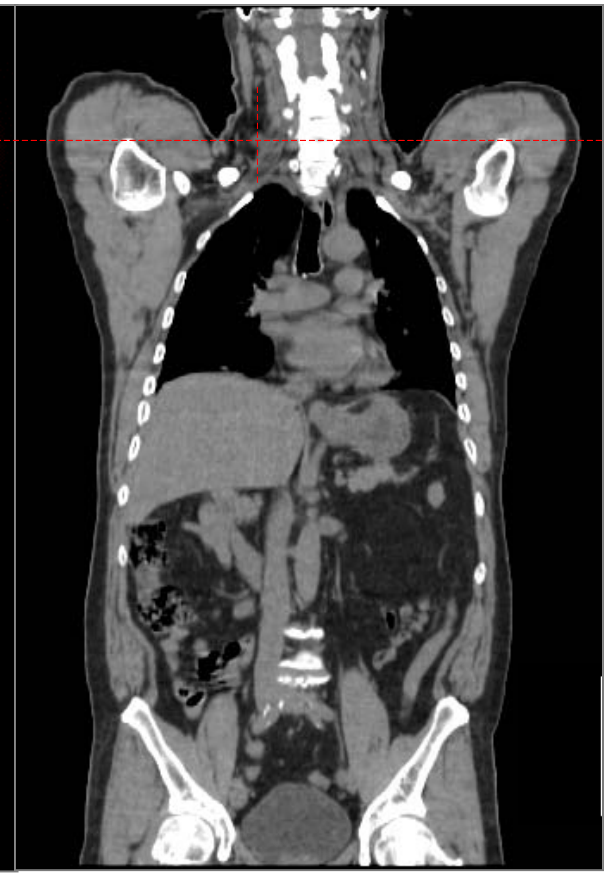


Imaging FDG uptake (PET) & anatomical localization (CT)

Function



Function+Anatomy and CT-based attenuation correction



Anatomy

Diagnostic Accuracy of PET/CT exceeds CT or PET only

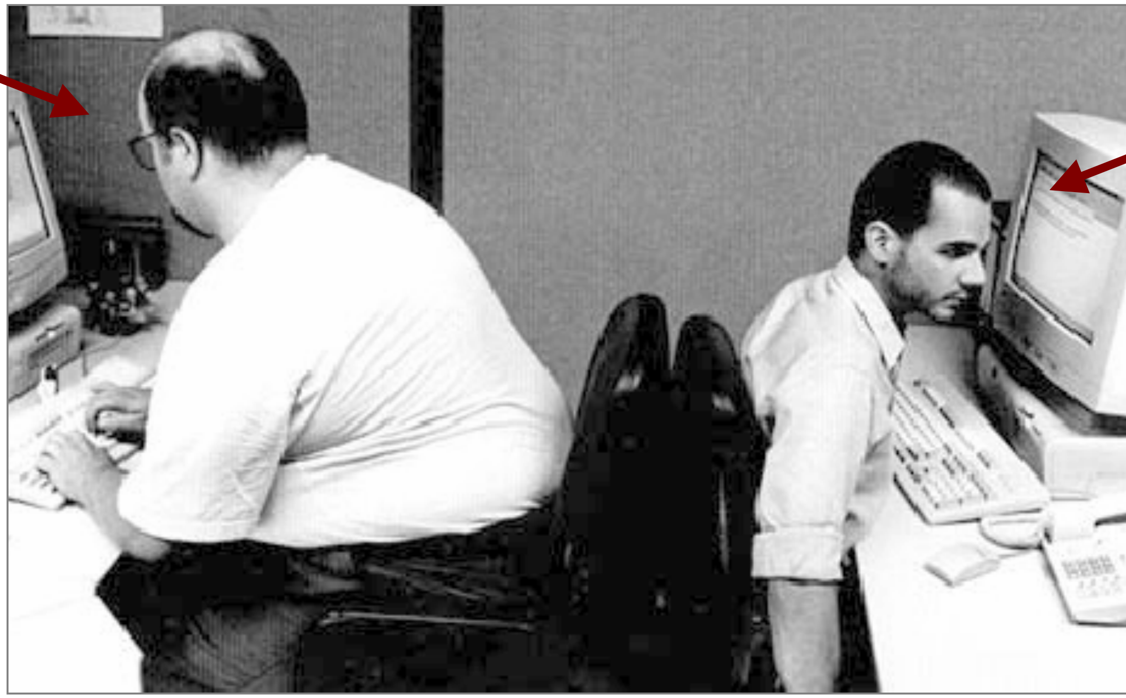
Tumor entity	References	Purpose of the imaging studies	Number of patients	Accuracy (%)		
				PET/CT	PET	CT
Head and neck	Chen *et al*. (2006)[35]	TNM staging	70	95	83[a]	73[a]
	Schoder *et al*. (2004)[36]	Lesion detection	68	96	90[a]	ND
NSCLC	Lardinois *et al*. (2003)[24]	T stage N stage	40 37	98 84	80[a] 87	78[a] 64
	Shim *et al*. (2005)[37]	T stage N stage	106 106	86 84	ND ND	79 69[a]
Colorectal	Kim *et al*. (2005)[10]	Recurrence	51	88	71[a]	ND
	Votrubova *et al*. (2006)[38]	Recurrence	84	90	75[a]	ND
Lymphoma	Allen-Auerbach *et al*. (2004)[33]	(Re)staging	73	93	84[a]	ND
	la Fougère *et al*. (2006)[39]	(Re)staging	50	99	98	89[a]
Melanoma	Reinhardt *et al*. (2006)[31]	(Re)staging	250	97	93[a]	79[a]
	Mottaghy *et al*. (2007)[40]	(Re)staging	102	91	92	ND

[a]Statistically significant difference when compared with PET/CT. Abbreviations: NSCLC, non-small-cell lung cancer; ND, not determined; TNM, tumor node metastasis.

Weber et al. Nature Reviews Clinical Oncology 2008

PET with ^{18}F-FDG is used for cancer imaging

Cancer diagnosis and staging



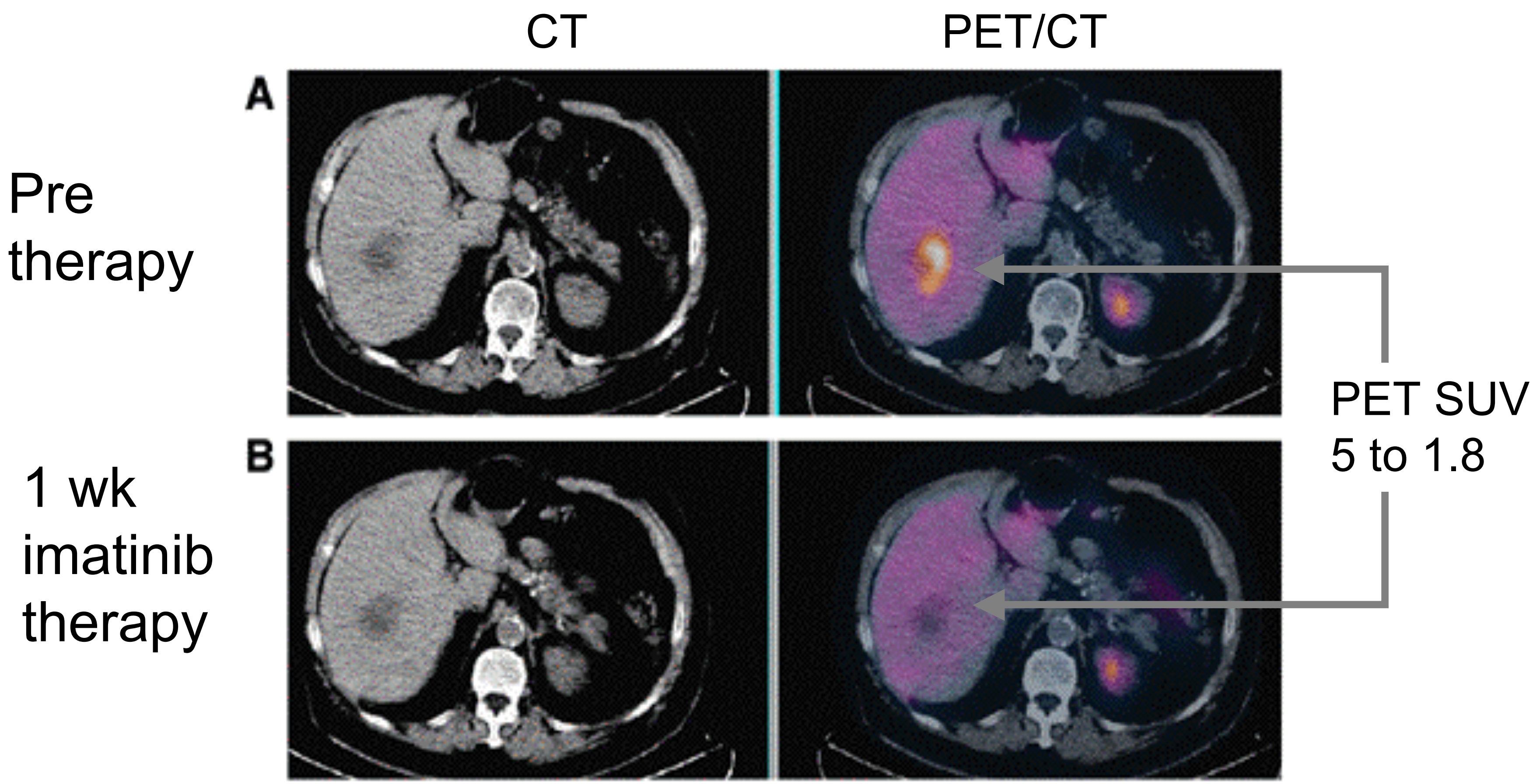
everything else

- Neuro
- Cardiac
- Therapy planning
- Therapy development

- Currently ~ 92% of all PET/CT studies are for diagnosis and staging in oncology imaging
- About 5000 scanners world wide
- 2.5 millions scans done annually in US

Response to therapy of liver met gastric GIST

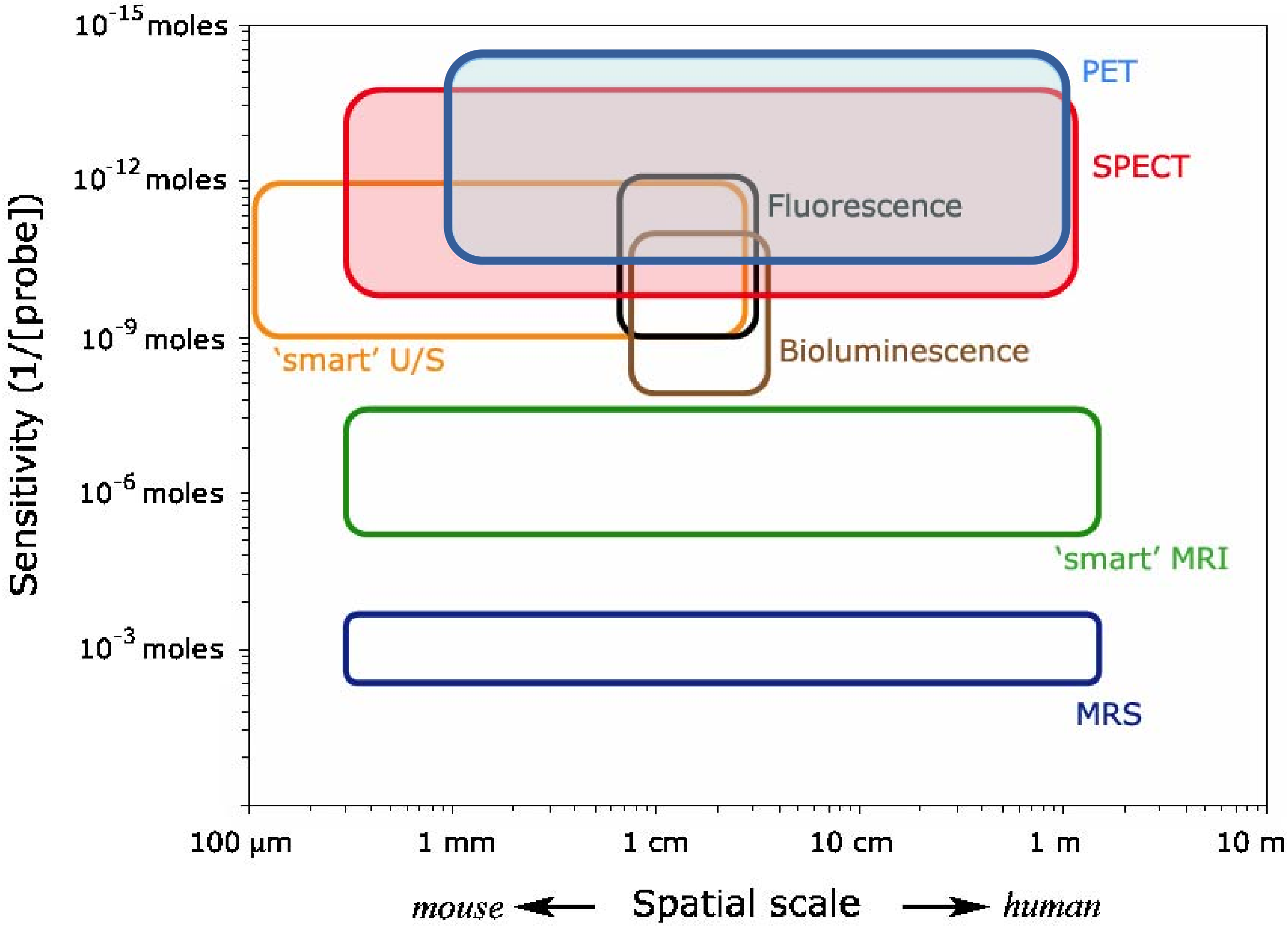
No morphological change in the metastasis



Castell and Cook, British J Cancer 2008

What are the advantages of PET/CT?

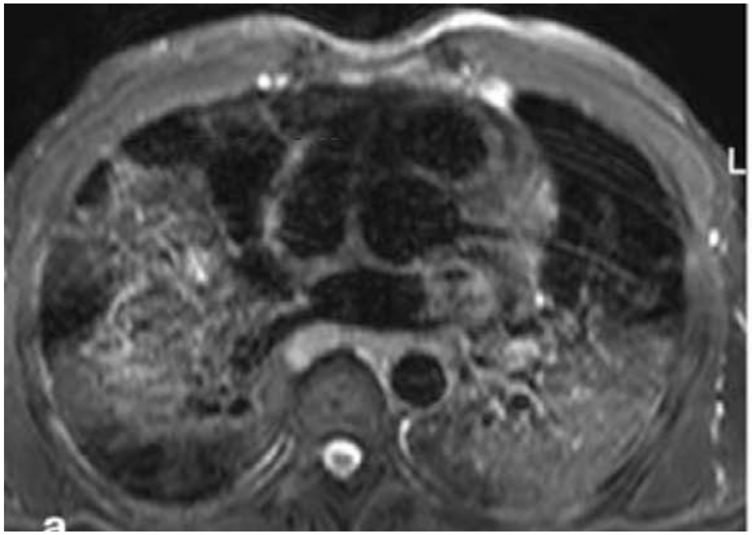
Sensitivity

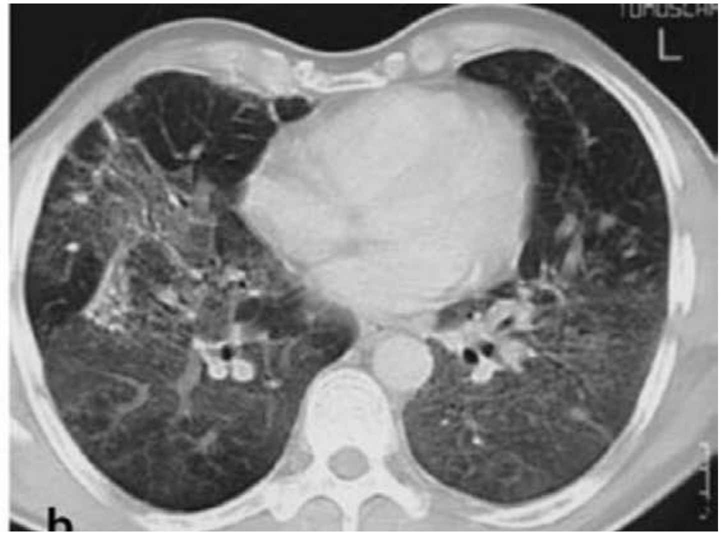


Meikle PMB 2005

Quantitation

MR

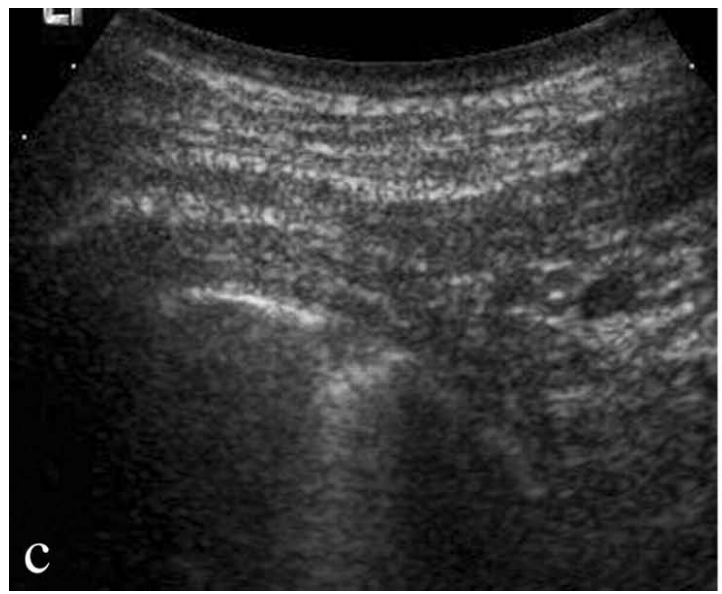




CT

What do the image values represent?

PET

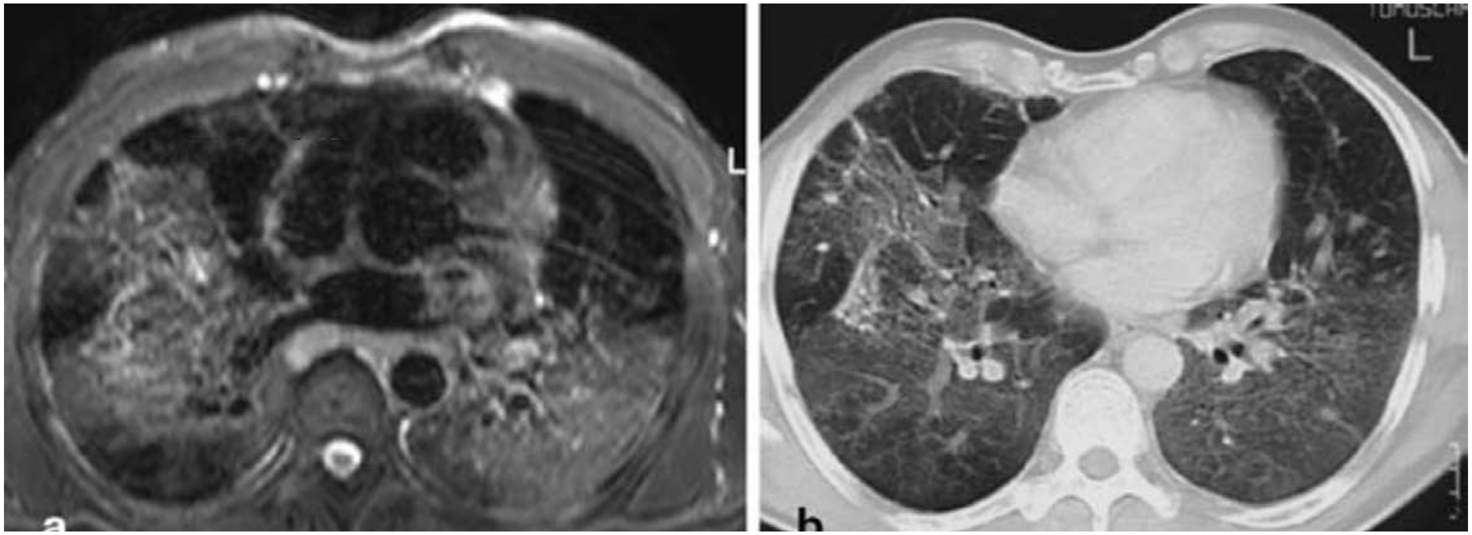


US

Linear with position and tracer concentration

Quantitation

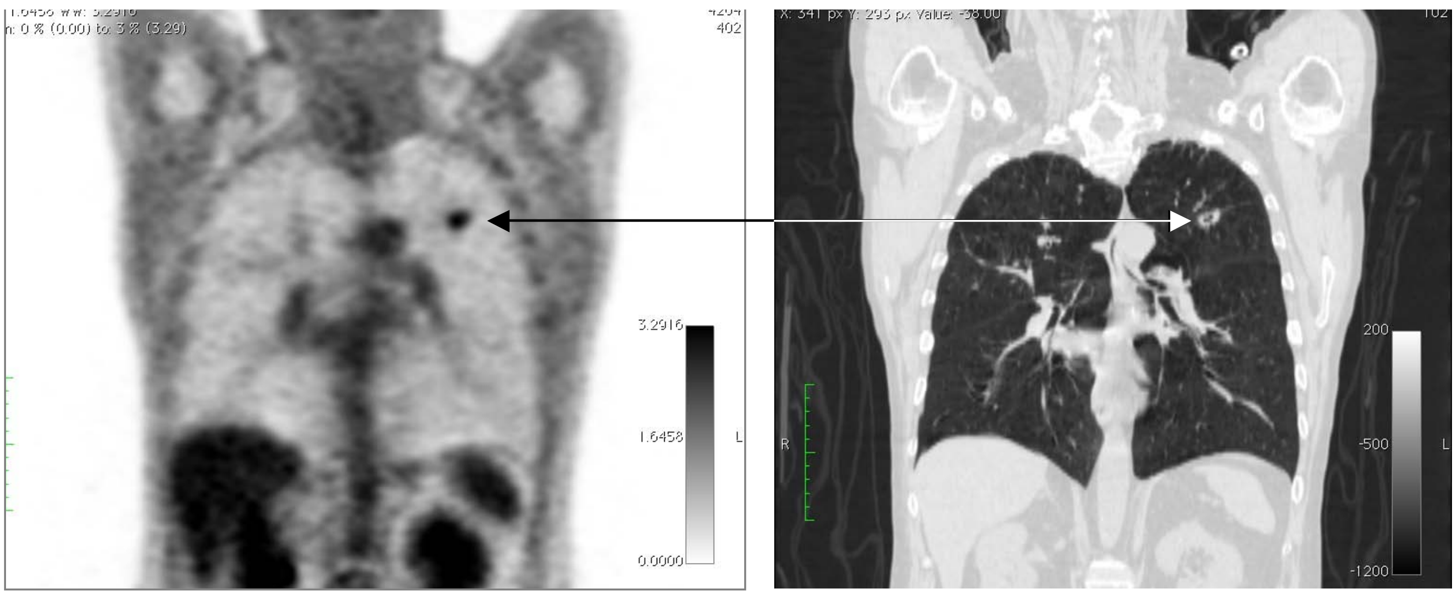
MR



CT

What do the image values represent?

PET



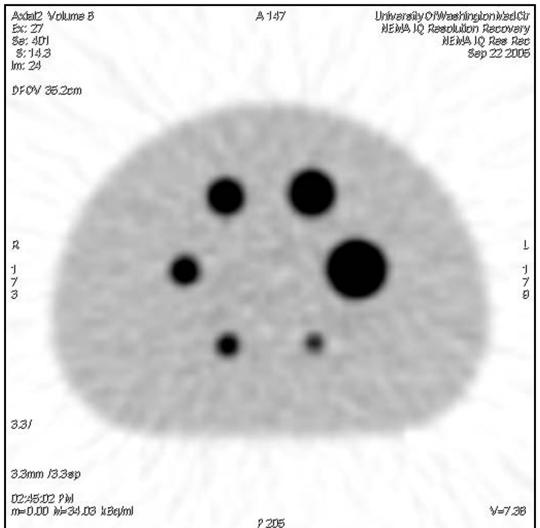
CT

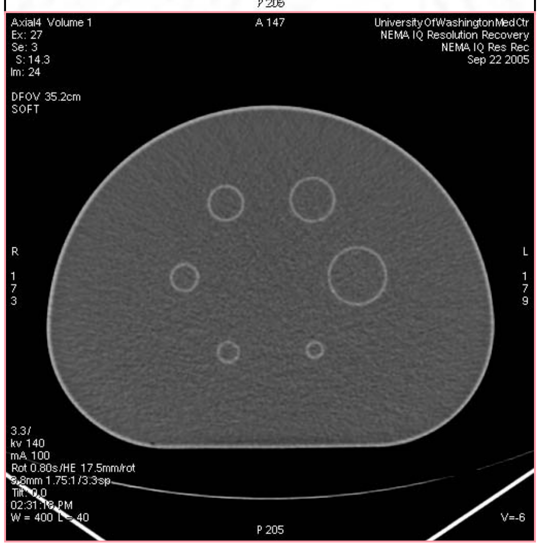
Linear with position and tracer concentration

Linear with position

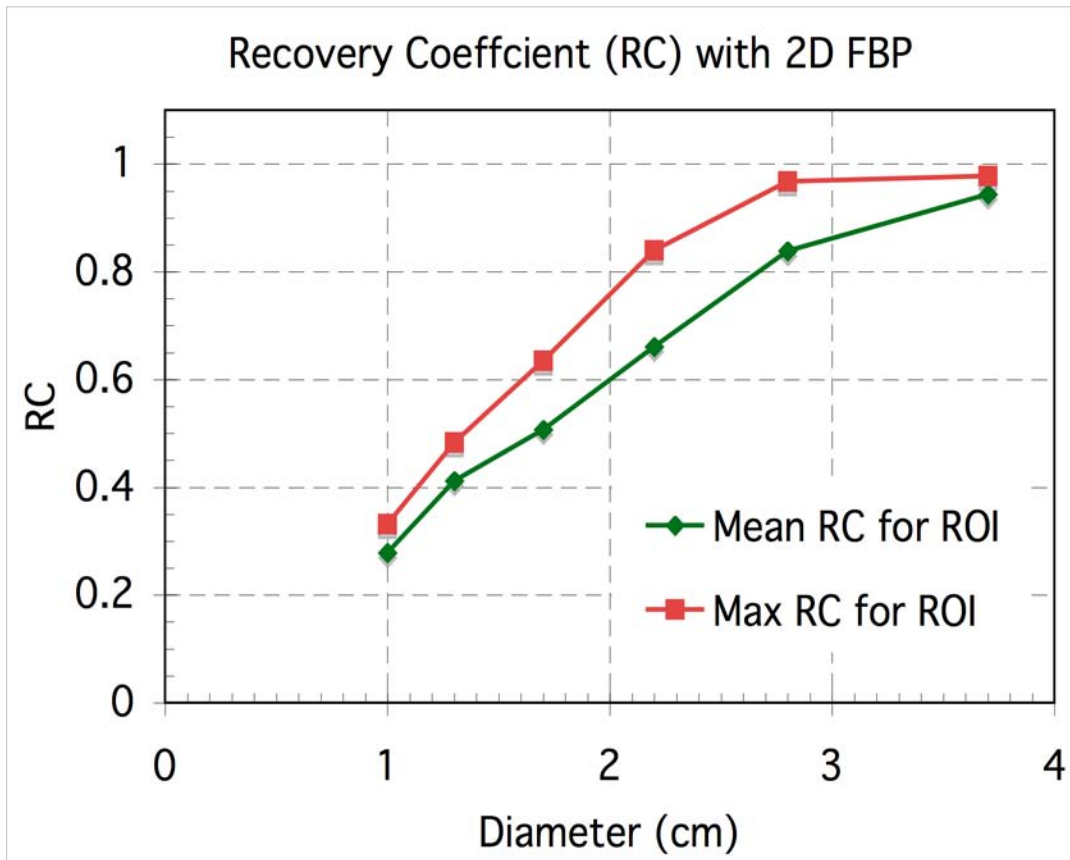
Improvements and/or Artifacts

Resolution Effects





- Modified NEMA NU-2 Image Quality Phantom (30 cm x 23 cm cross section)
- Sphere diameters:1.0, 1.3, 1.7, 2.2, 2.8, 3.7 cm
- 4:1 target:background ratio and typical patient activity
- RC = measured / true



Resolution Effects

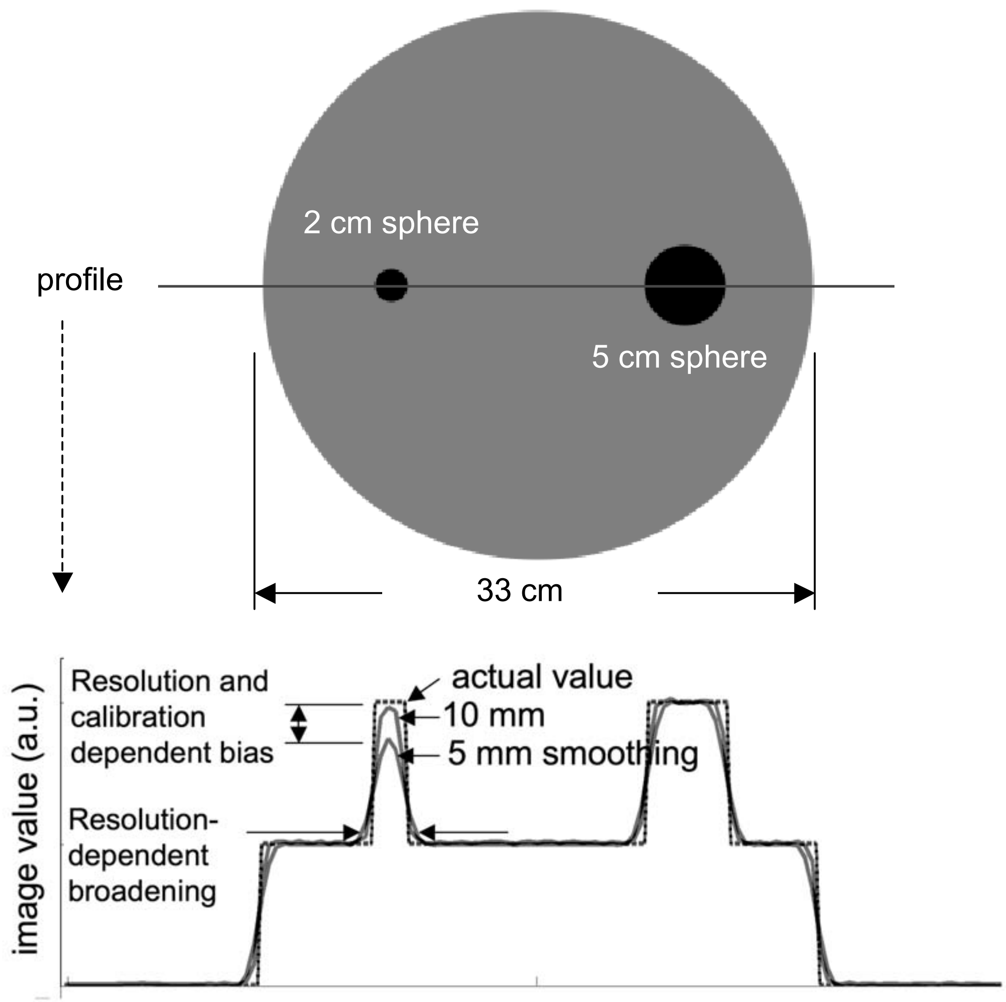
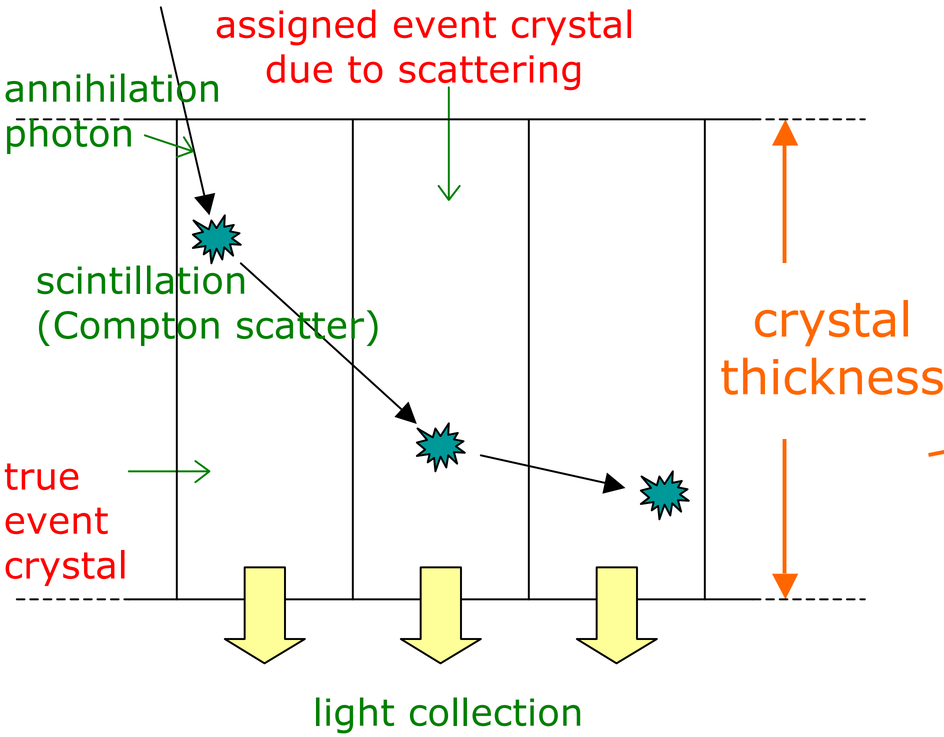
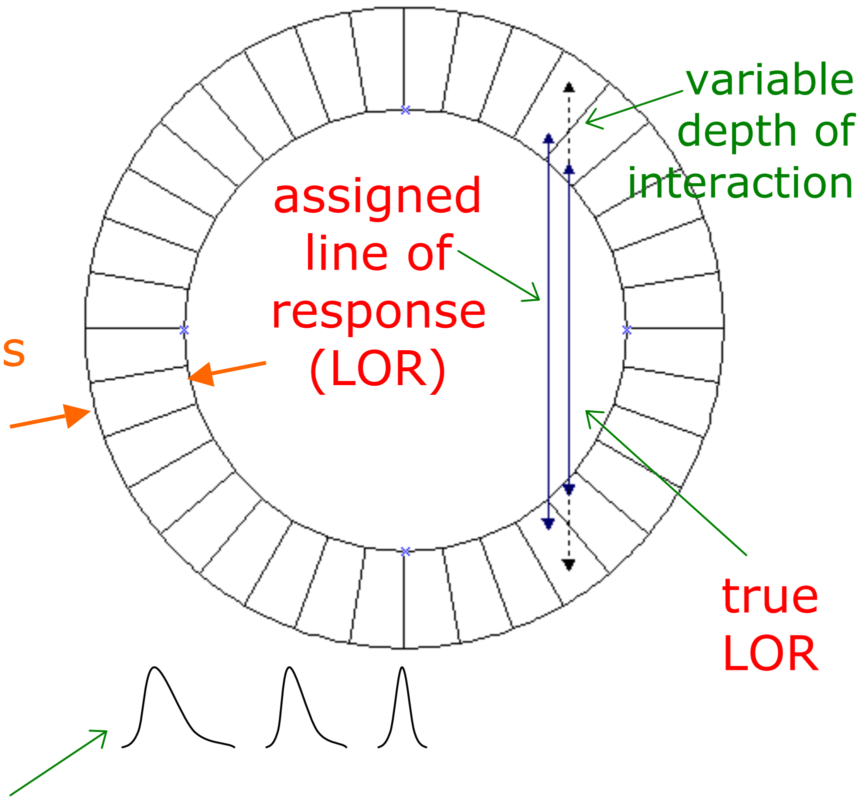


Image Reconstruction: Modeling Detector Blurring

Inter-crystal scattering



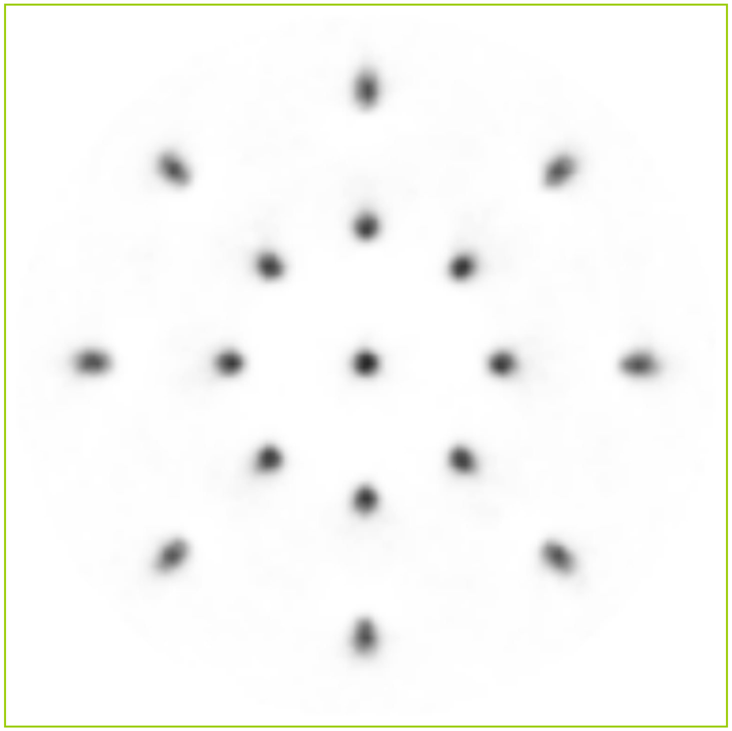
Parallax error



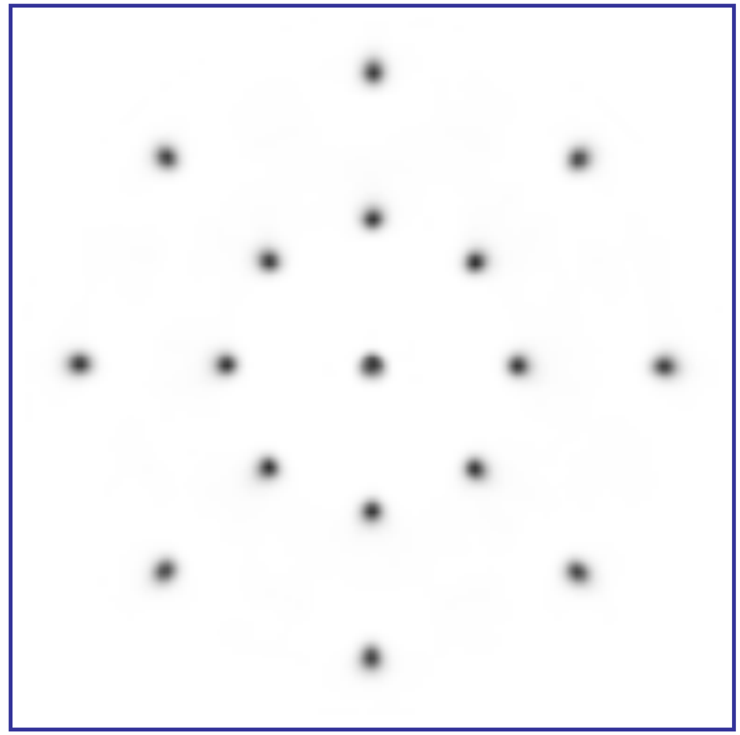
Shape of detector blurring point spread function (PSF)

- Radially variant
- Asymmetric in transaxial direction
- Two-fold symmetric about FOV center

Spatially-Variant Image Resolution



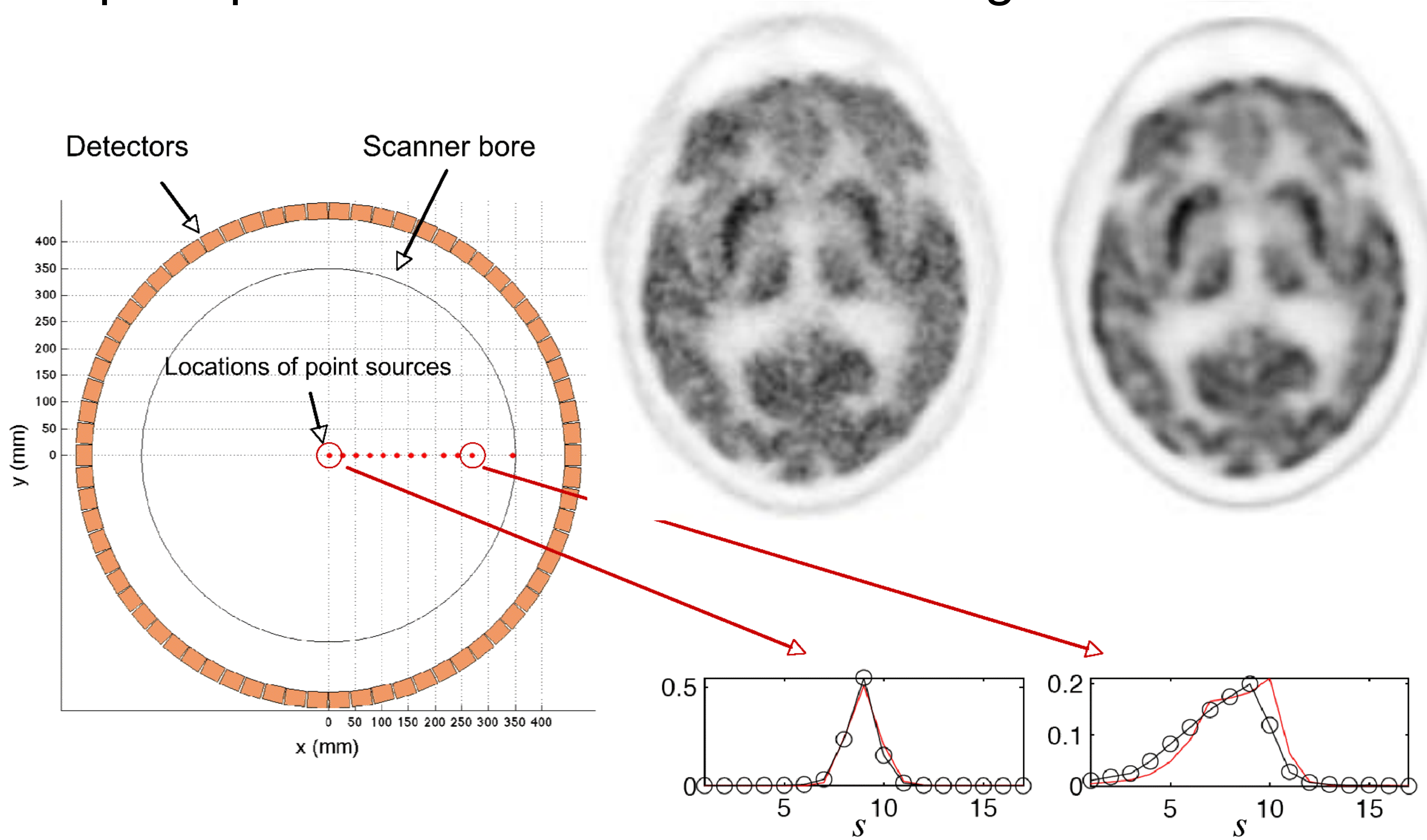
standard
OSEM



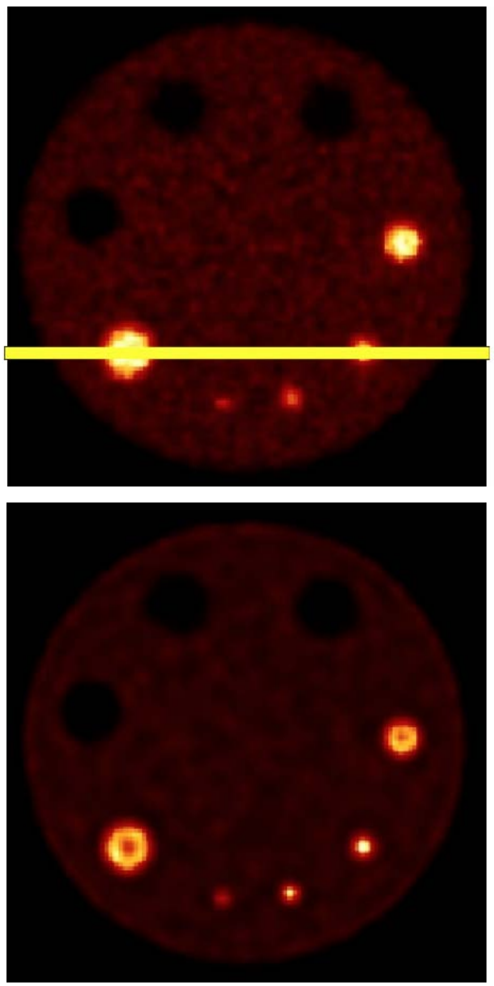
OSEM with
detector blurring
modeled

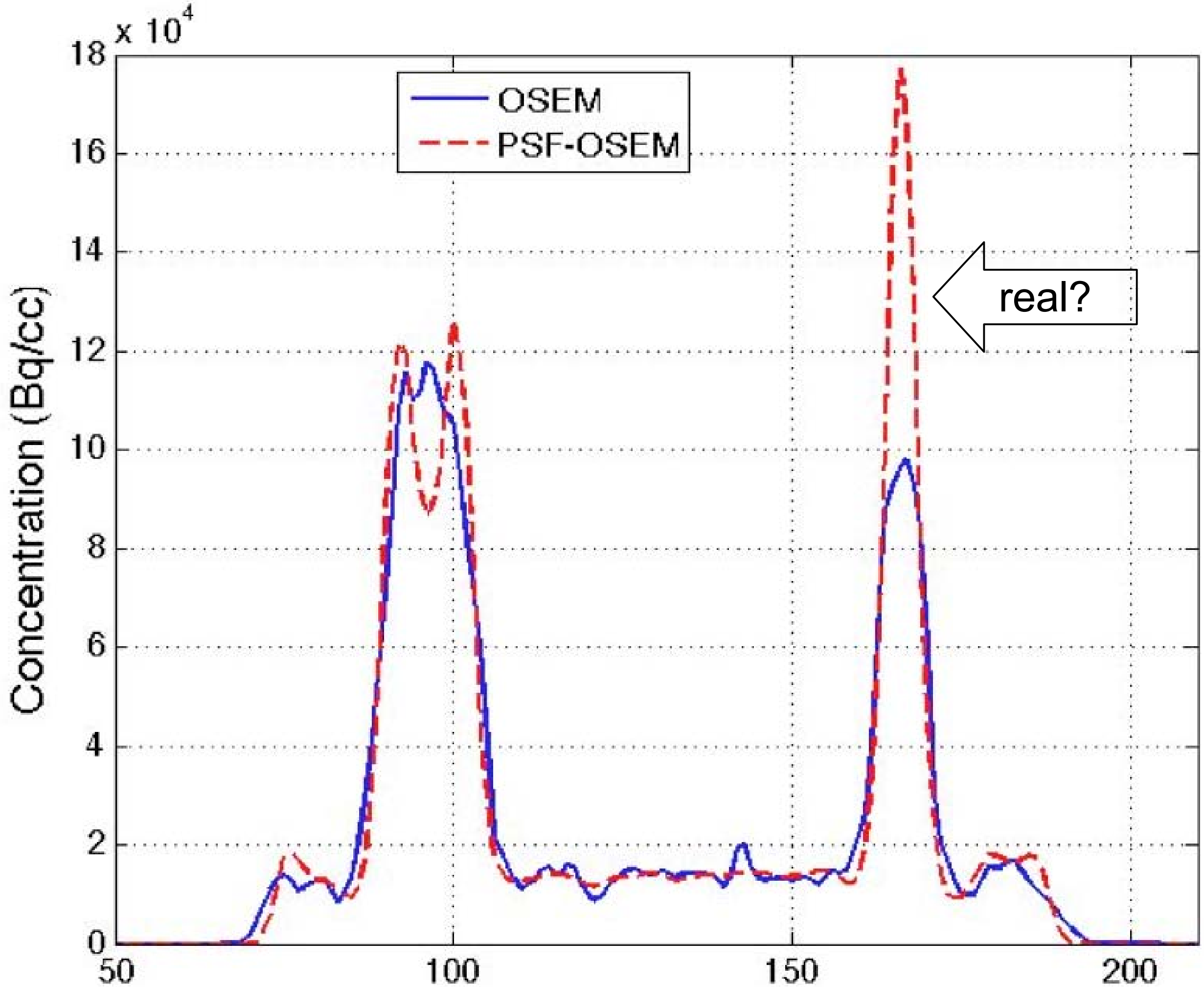
Including improved physics modeling in image reconstruction

- In principle can remove detector blurring



Phantom measurements: ringing artifact

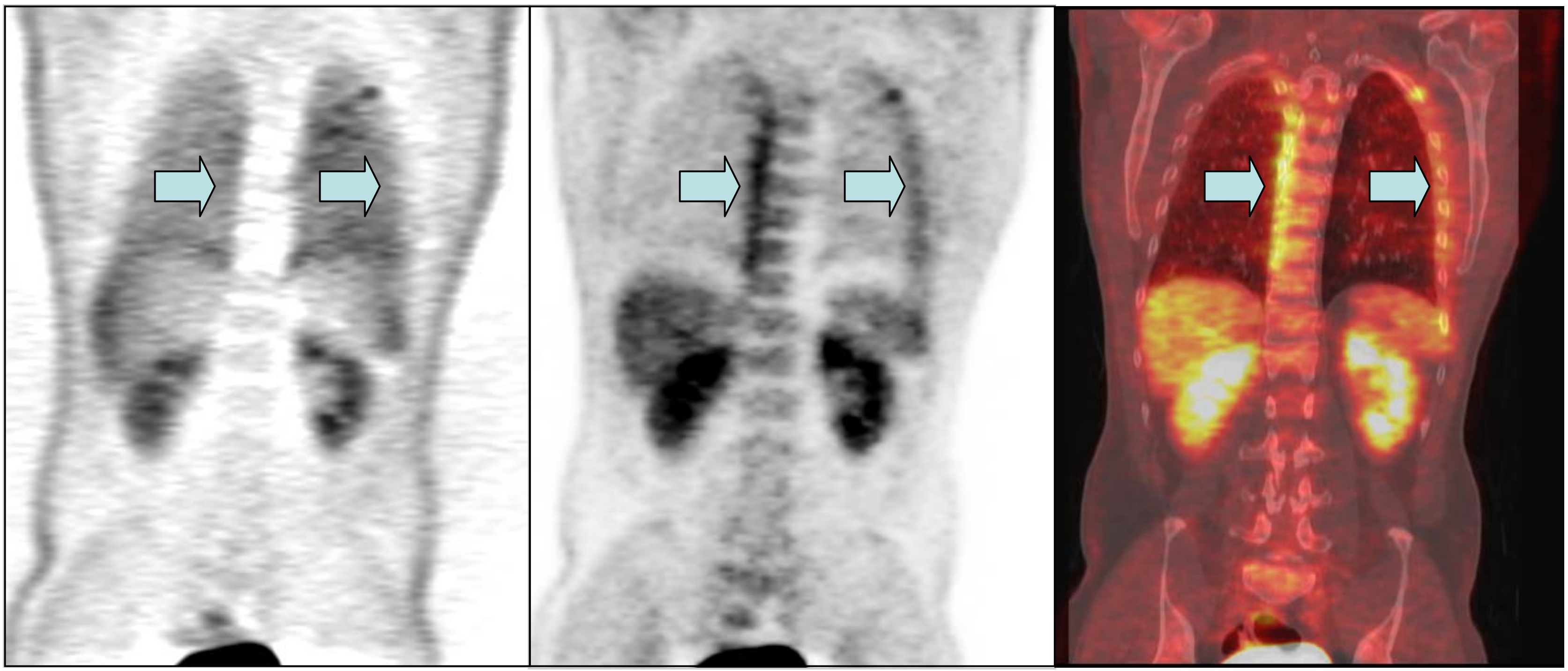




Bai, 2010 IEEE MIC conf record

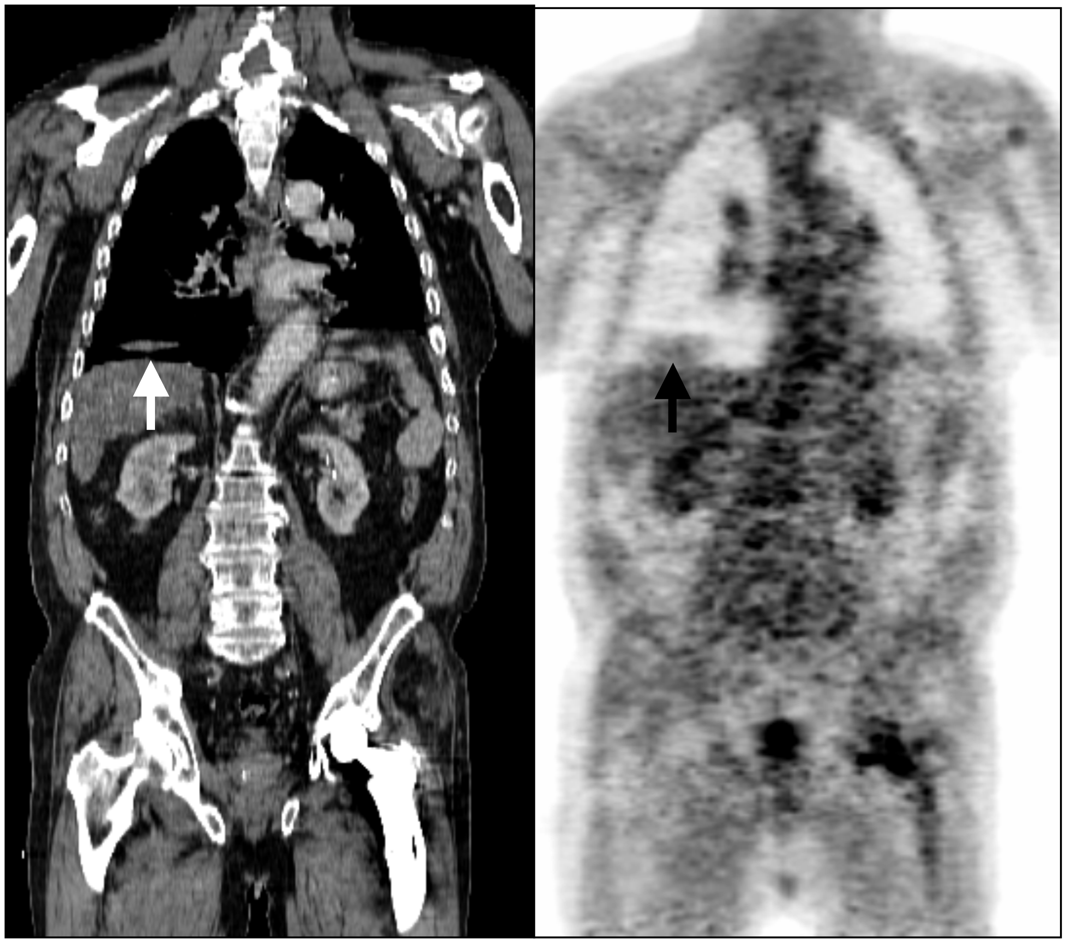
Patient shifting

- Large change in attenuation going from spine to lung



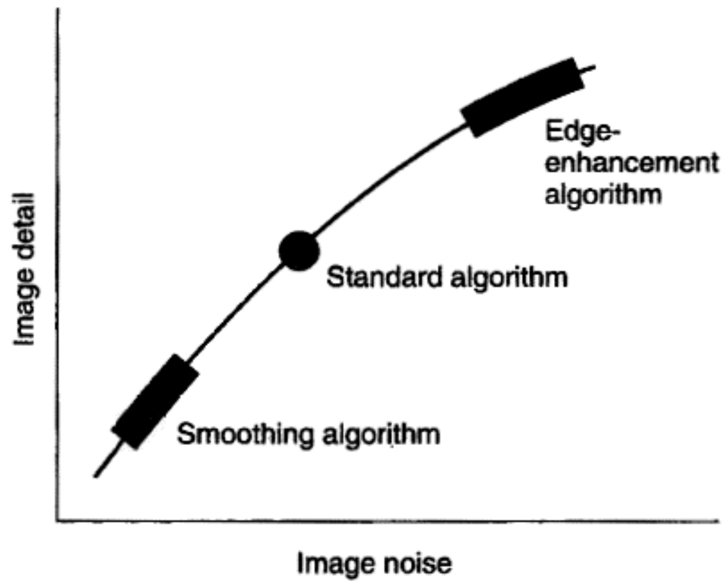
?

Breathing Artifacts: Propagation of CT breathing artifacts via CT-based attenuation correction



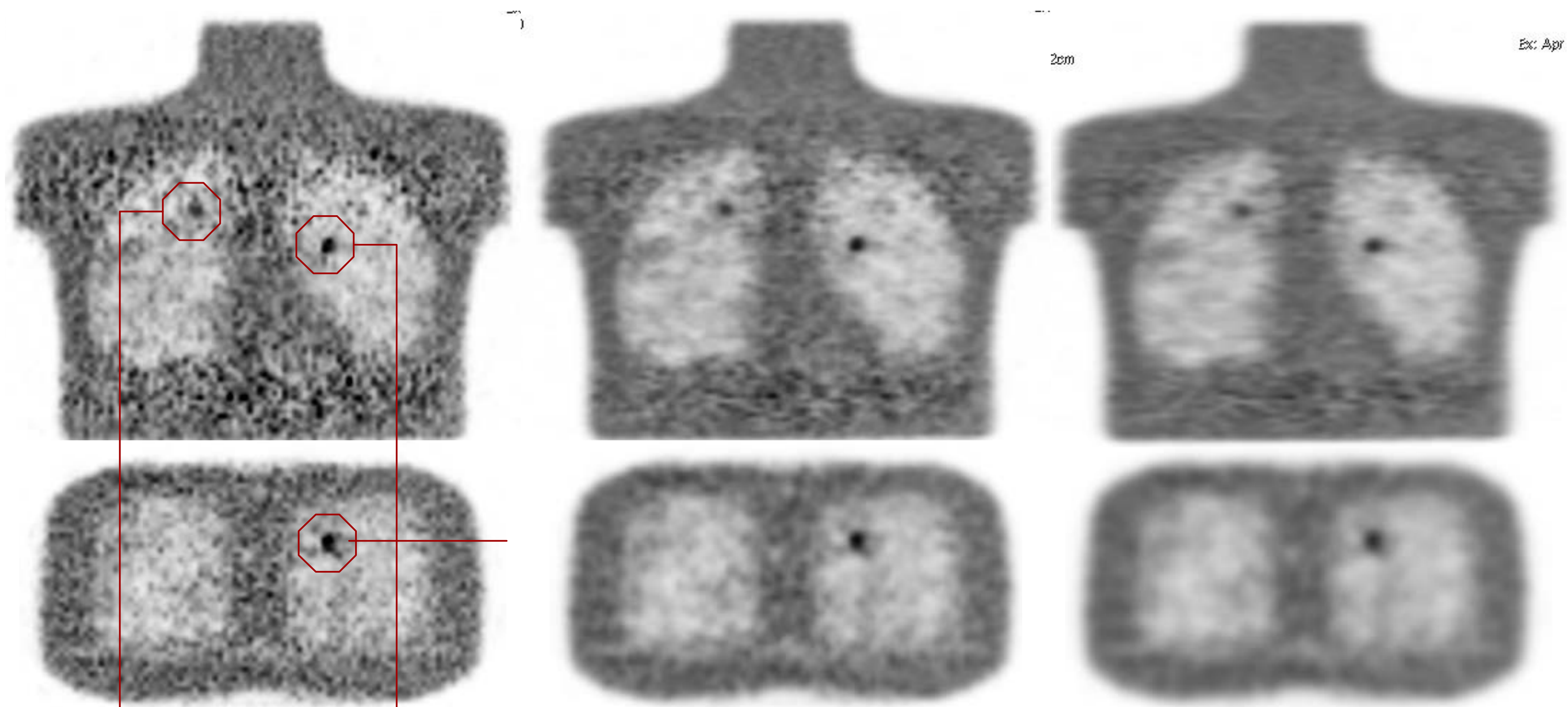
Attenuation artifacts from CT can dominate true PET tracer uptake values

Image Smoothing: Noise vs. Resolution



- Always a trade-off in noise vs. resolution
- The choice of the best filter to use with the reconstruction algorithm depends on the clinical task
- There are no standards for choice of smoothing

Effect of changing smoothing



4 mm smoothing → 7 mm smoothing → 10 mm smoothing

RC for 1 cm spheres

4 mm smoothing	7 mm smoothing	10 mm smoothing
0.85	0.52	0.40
0.92	0.80	0.72

SNM Chest phantom: True RC is 1.0

Image Quality

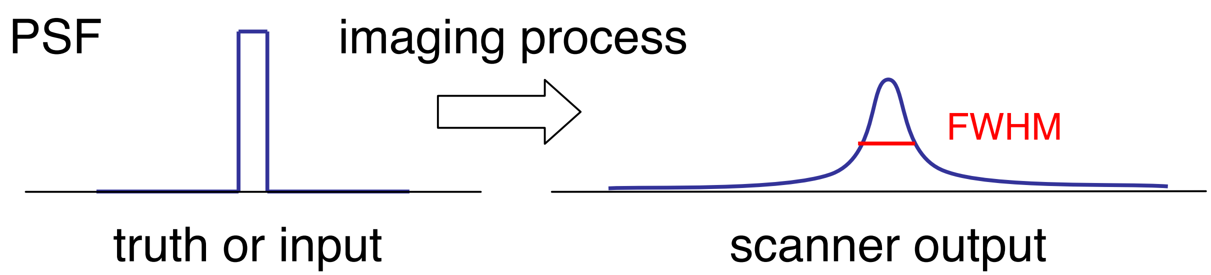
Image Quality

Image quality, for the purposes of medical imaging, can be defined as the ability to extract desired information from an image

- Harrison H. Barrett *PNAS, 1993*

Traditional measures: Resolution

- Point-spread function (PSF): Narrower is better
- Modulation transfer function (MTF), which is the absolute value of the frequency-space version of the PSF: Wider is better



- FWHM, FWTM, FW100M, etc - but these can only approximate the PSF
- Bias is related to the PSF, but in a non-trivial way

Traditional measures: Noise

- Sensitivity: response to very low activity levels
- More counts -> lower noise -> Better SNR
- Noise Power Spectrum: noise power at each frequency
- Note that *apparent* noise in a single image, is not necessarily the same as *true* noise measured from multiple images.

Law of conservation of difficulty

- There are always trade-offs: In this case usually noise vs. resolution or bias
- looking at the range of values is important to be fair
- looking at the operating point may be the most important, but can be difficult to determine

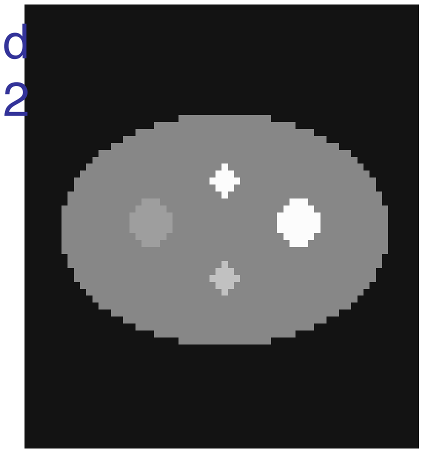
How do you compare images?

- define task
  - detection
  - localization
  - estimation (quantitation)
  - shape discrimination
  - combinations of the above, etc.
- measure (quantitate) task performance
- these are often time consuming studies and can be difficult to perform properly
- we can in some cases use computer models of human performance -- so called ‘model’ or ‘computational’ observers -- that are based on the human perceptual system

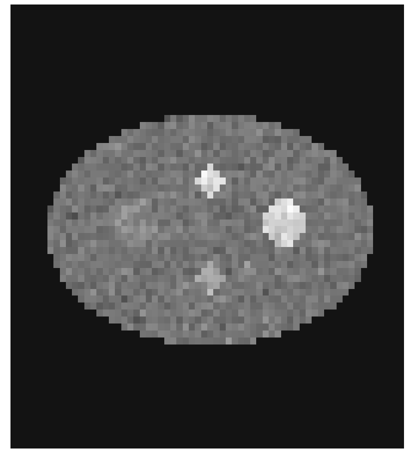
Detectability: Is it there?

lesion:background
1 : 1.2 : 1.5 : 2

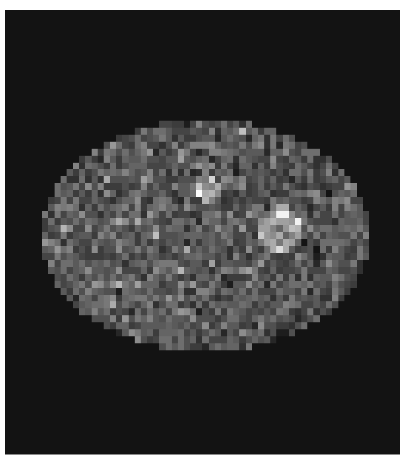
Noiseless



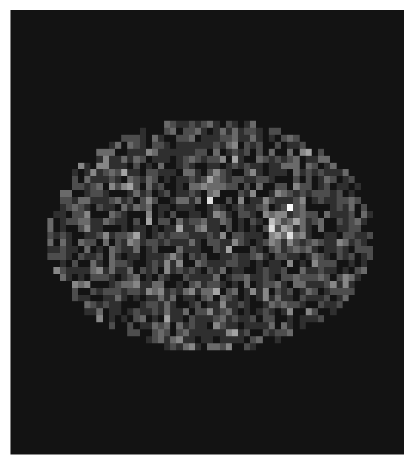
100 kcounts



10 kcounts

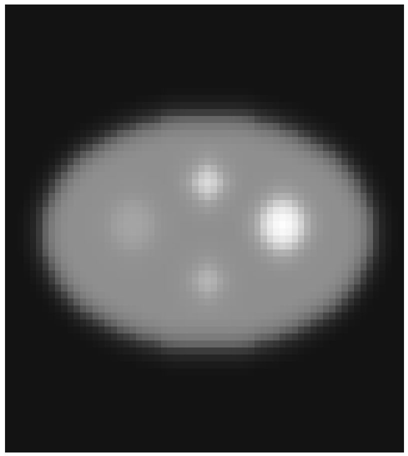


2 kcounts

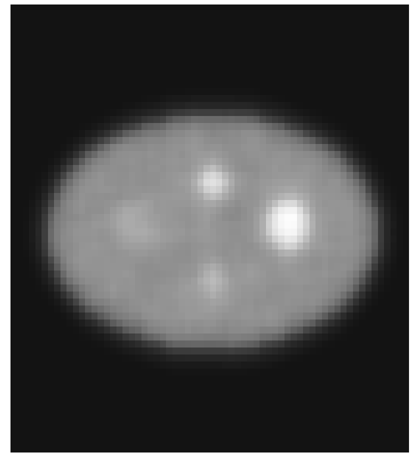


Decreased resolution

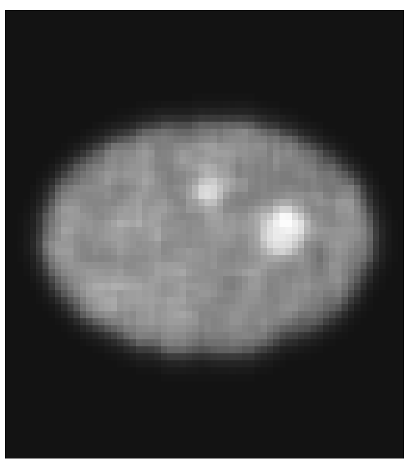
Noiseless



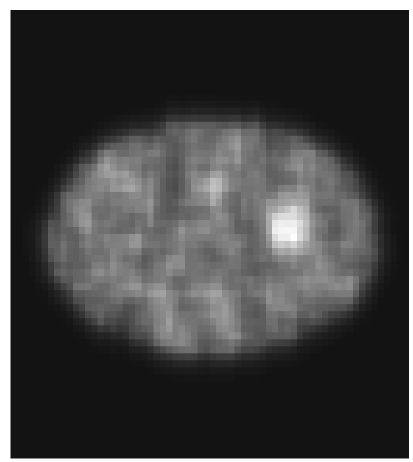
100 kcounts



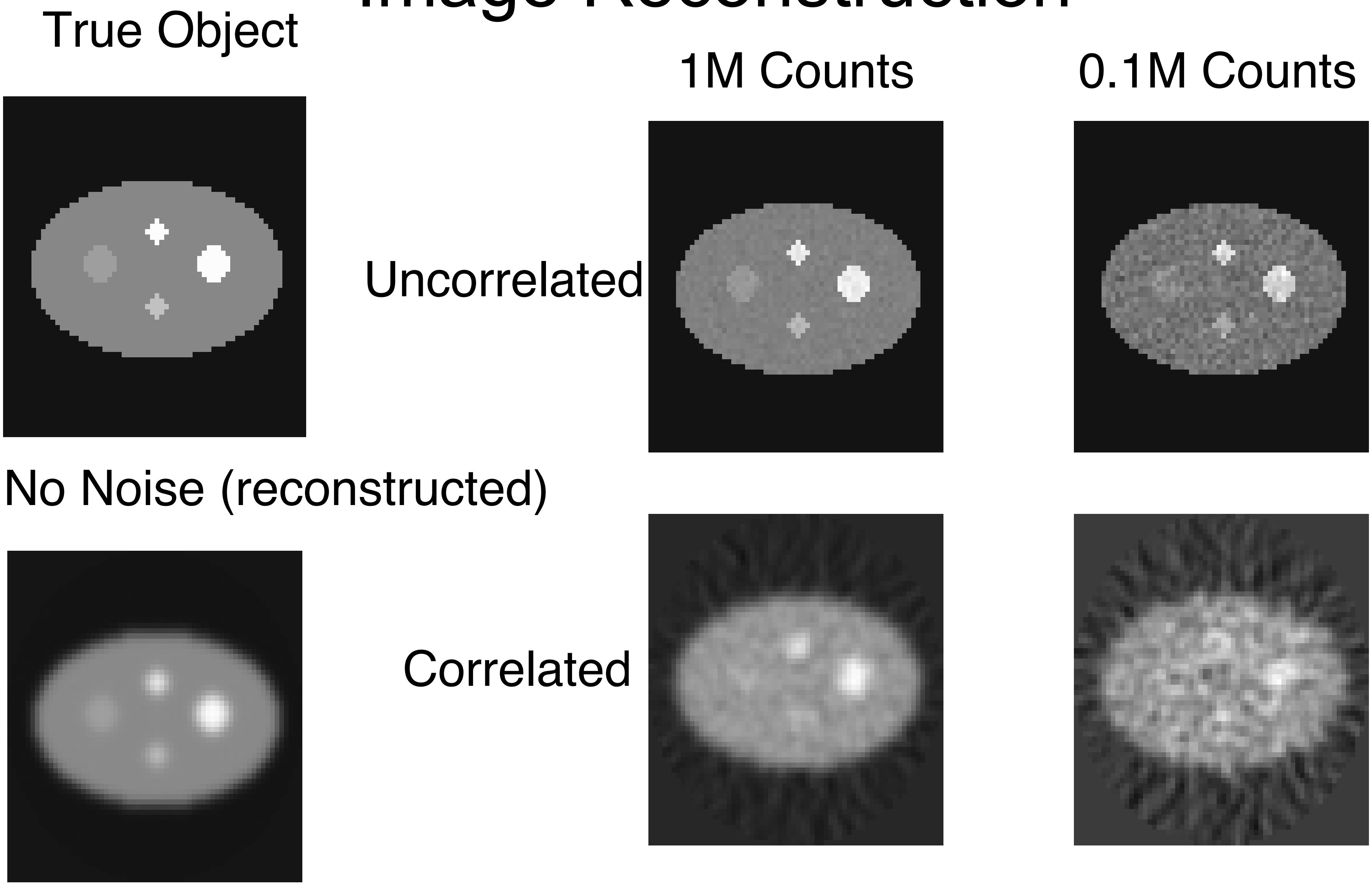
10 kcounts



2 kcounts



Correlated Noise Introduced by Image Reconstruction



Resolution Effect of Smoothing vs. Noise

Human abdomen simulation with 2cm diam. lesion 2:1 contrast

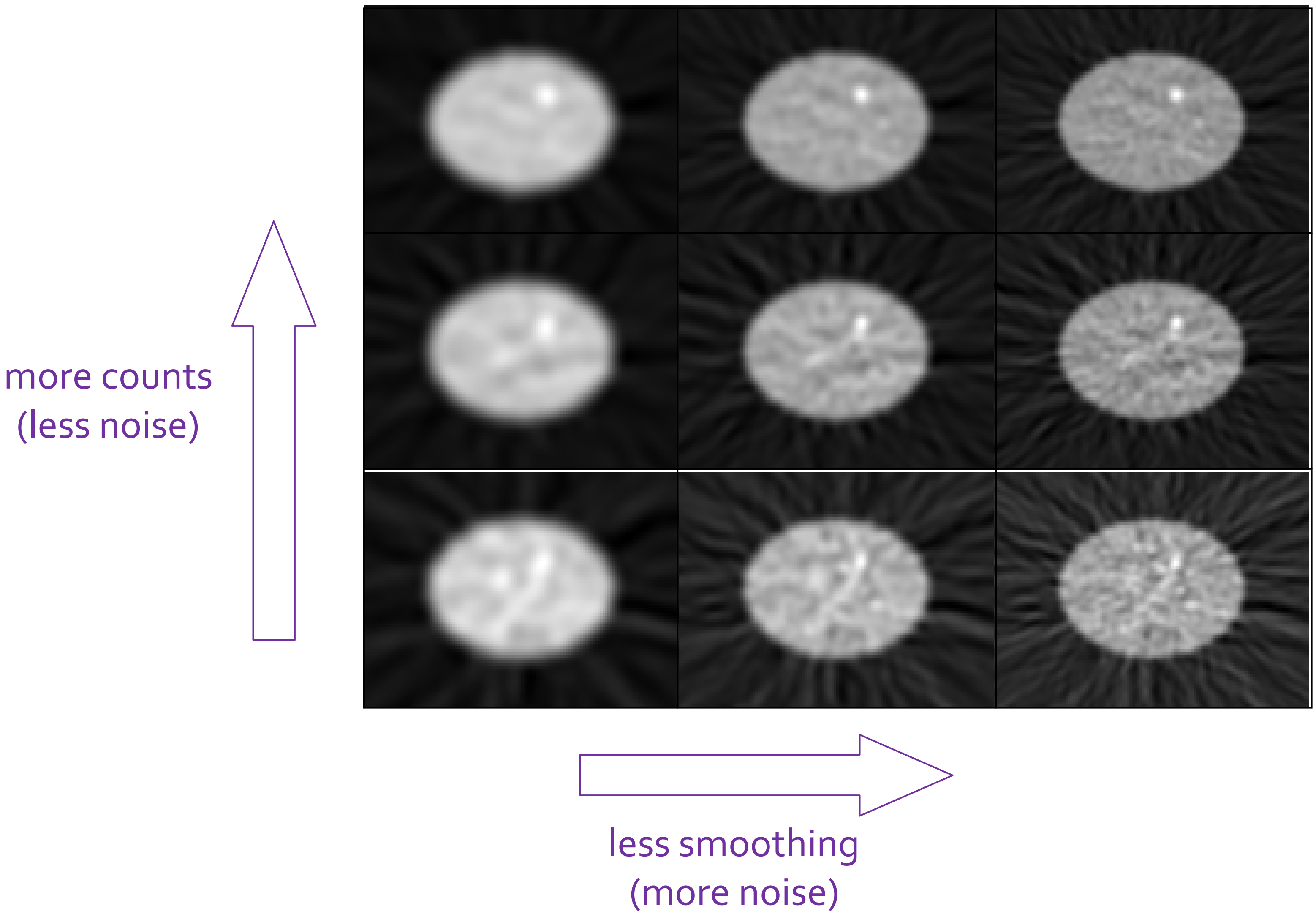


Image Quality

Image quality, for the purposes of medical imaging, can be defined as the ability to extract desired information from an image

- Harrison H. Barrett *PNAS, 1993*

Diagnostic Accuracy of PET/CT exceeds CT or PET only

Tumor entity	References	Purpose of the imaging studies	Number of patients	Accuracy (%)		
				PET/CT	PET	CT
Head and neck	Chen *et al*. (2006)[35]	TNM staging	70	95	83[a]	73[a]
	Schoder *et al*. (2004)[36]	Lesion detection	68	96	90[a]	ND
NSCLC	Lardinois *et al*. (2003)[24]	T stage N stage	40 37	98 84	80[a] 87	78[a] 64
	Shim *et al*. (2005)[37]	T stage N stage	106 106	86 84	ND ND	79 69[a]
Colorectal	Kim *et al*. (2005)[10]	Recurrence	51	88	71[a]	ND
	Votrubova *et al*. (2006)[38]	Recurrence	84	90	75[a]	ND
Lymphoma	Allen-Auerbach *et al*. (2004)[33]	(Re)staging	73	93	84[a]	ND
	la Fougère *et al*. (2006)[39]	(Re)staging	50	99	98	89[a]
Melanoma	Reinhardt *et al*. (2006)[31]	(Re)staging	250	97	93[a]	79[a]
	Mottaghy *et al*. (2007)[40]	(Re)staging	102	91	92	ND

[a]Statistically significant difference when compared with PET/CT. Abbreviations: NSCLC, non-small-cell lung cancer; ND, not determined; TNM, tumor node metastasis.

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Acknowledgements

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