PET and PET-CT Imaging Physics

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Covering ABR Study Guide sections 17.L.(i)-(iv)

Positron Emission Tomography

- 3D imaging technique. Image brightness reflects:
- the concentration of positron-emitting radionuclides (e.g., F-18, O-15, C-11, N-13, Rb-82, I-124) labeled to a molecule of interest (e.g., F-18 FDG).
  Most have short half-lives: minutes to hours.
- Example: F-18-fluorodeoxyglucose

  - FDG is a glucose analog
  - transported from blood to tissue
  - hexokinase catalyzes phosphorylation of FDG to FDG-6-PO_4
  - not metabolized further, so it accumulates in cells and sticks
  - image reflects blood flow and metabolism

OUTLINE

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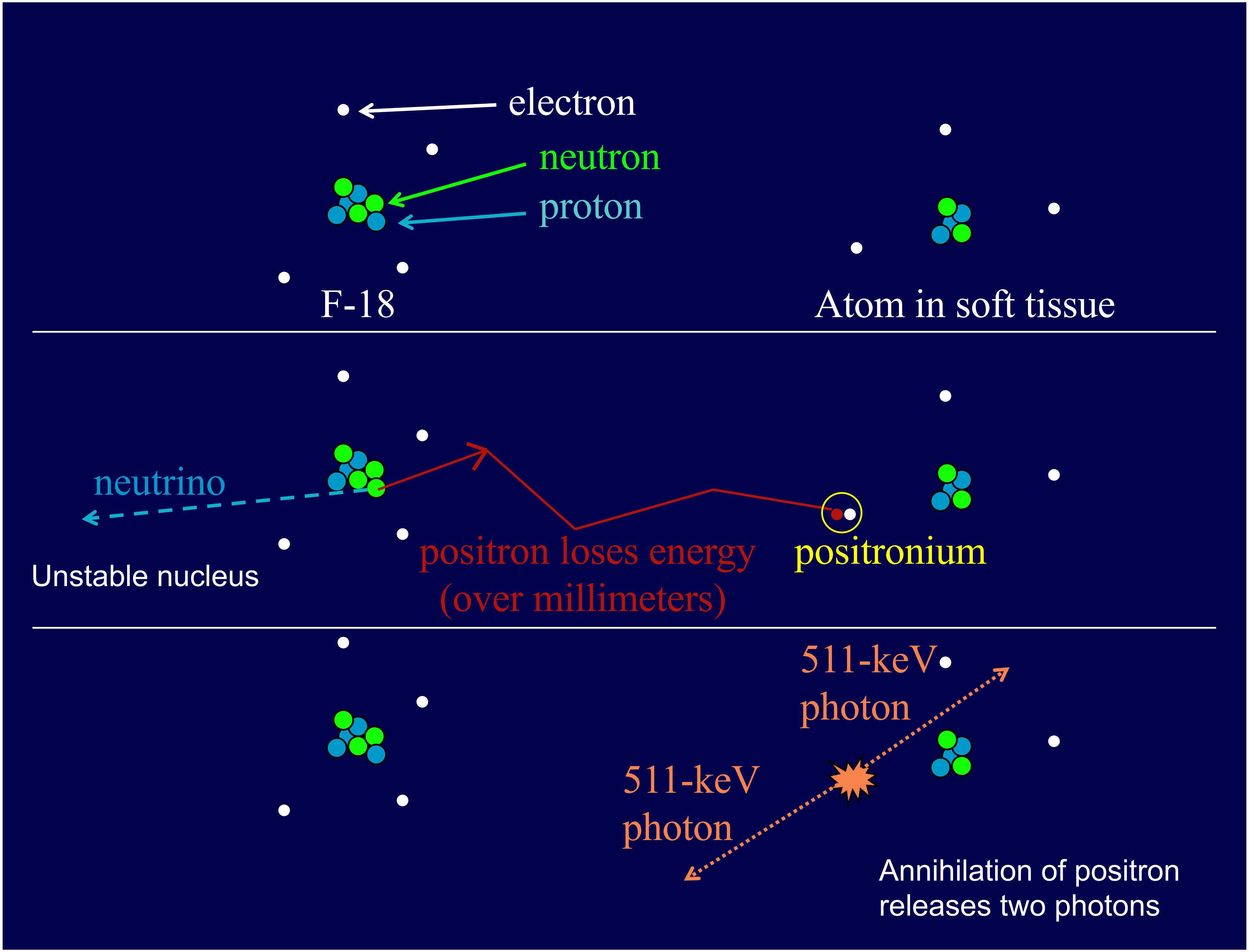
2. Coincidence detection, time of flight, and PET-CT
3. Quality control of PET systems
4. Types of events, randoms correction
5. Scatter correction
6. Attenuation correction from CT images
7. Spatial resolution and its correction
8. Standardized Uptake Values (SUV) and PV effect
9. Dynamic scans and kinetic analysis
10. QC requirements for accreditation


electron
neutron
proton
F-18
Atom in soft tissue
neutrino
Unstable nucleus
positron loses energy
(over millimeters)
positronium
511-keV
photon
511-keV
photon
Annihilation of positron
releases two photons

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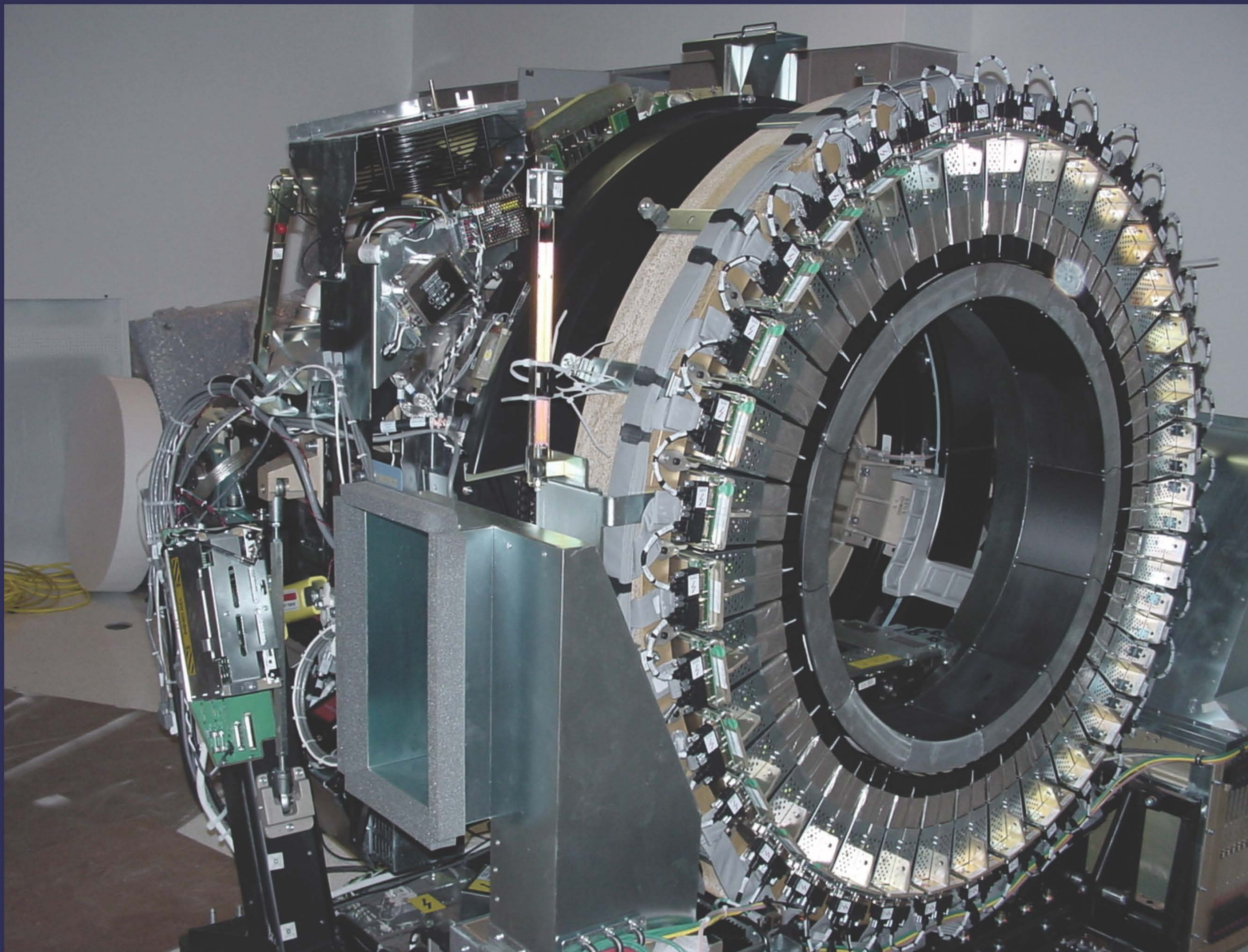
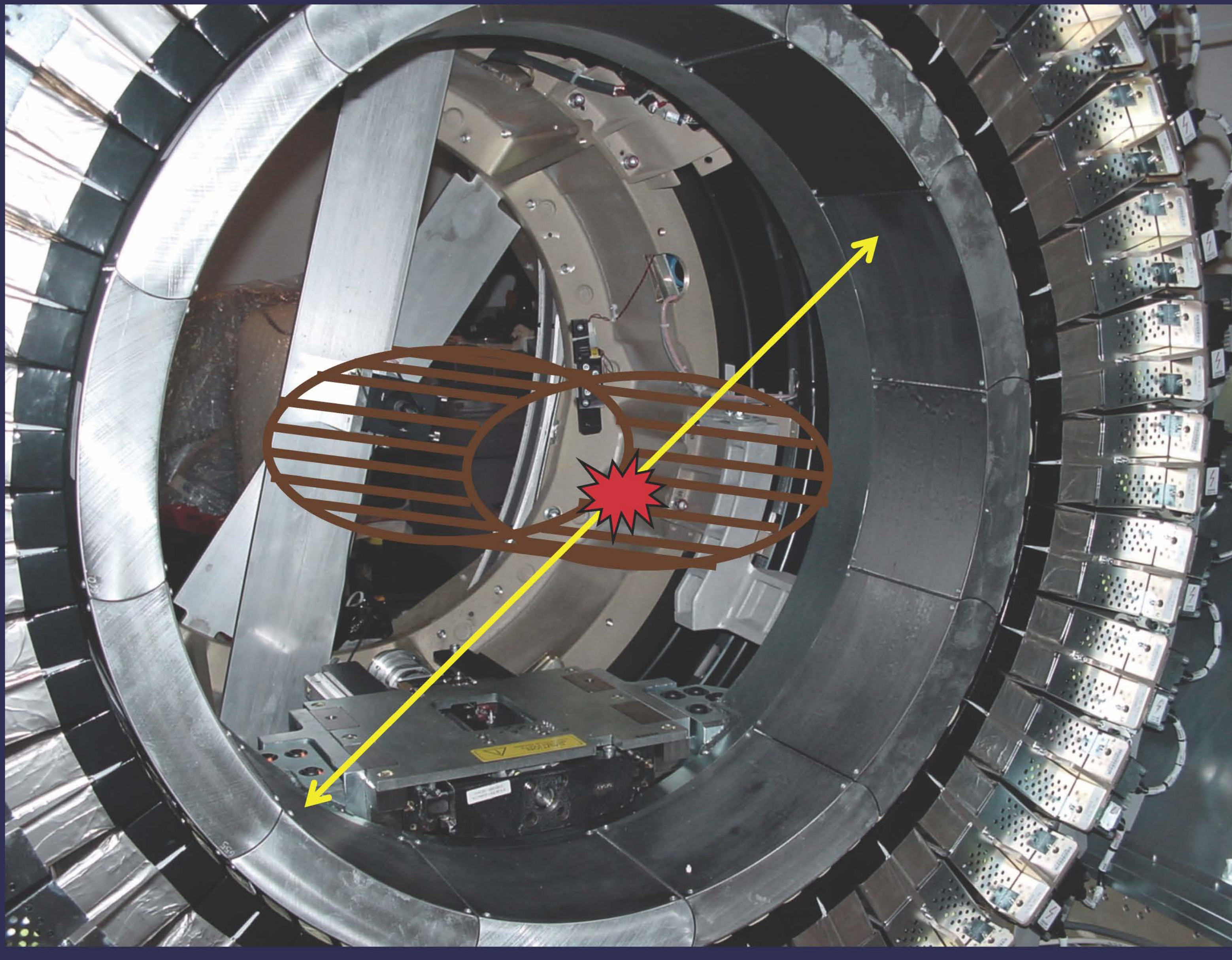
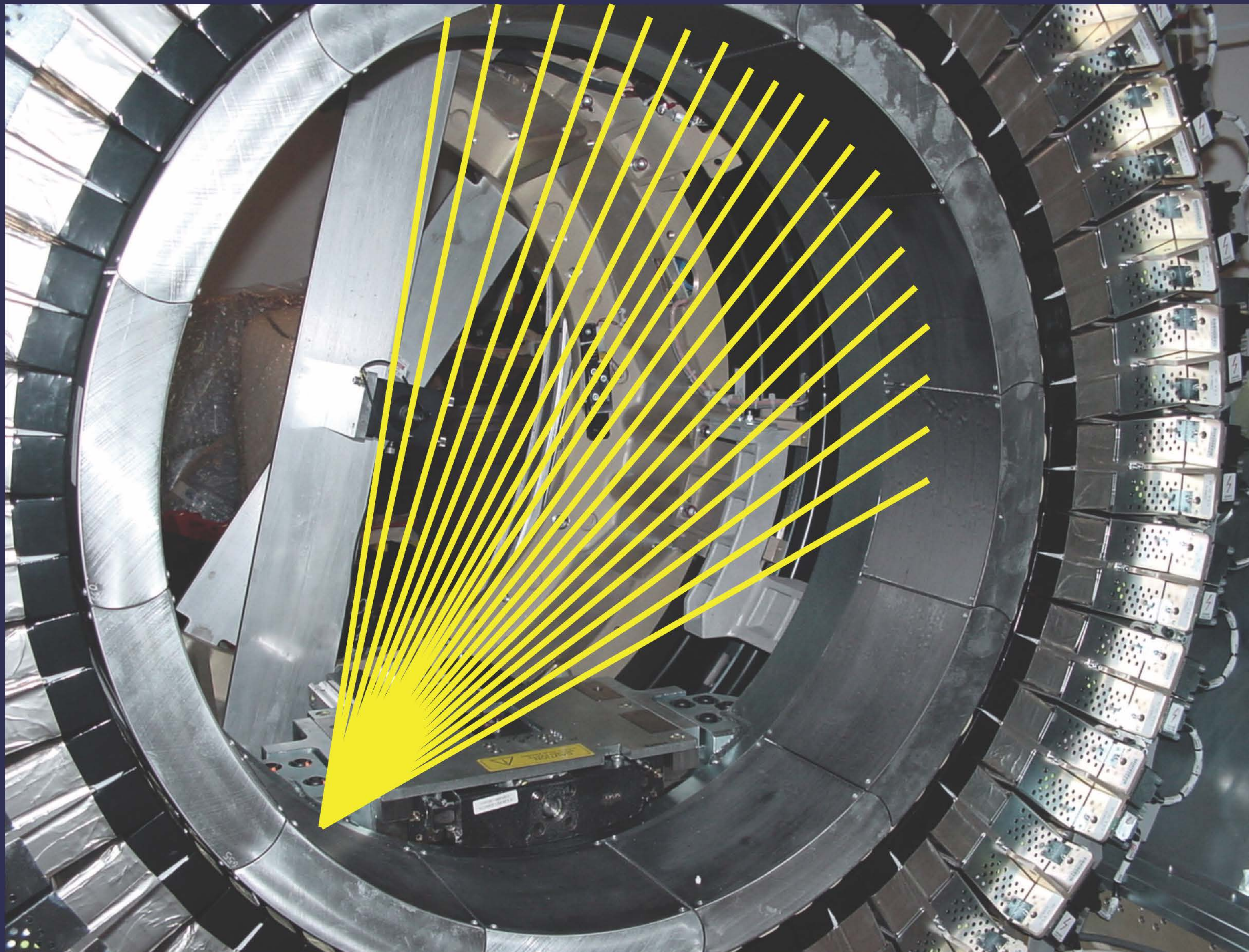
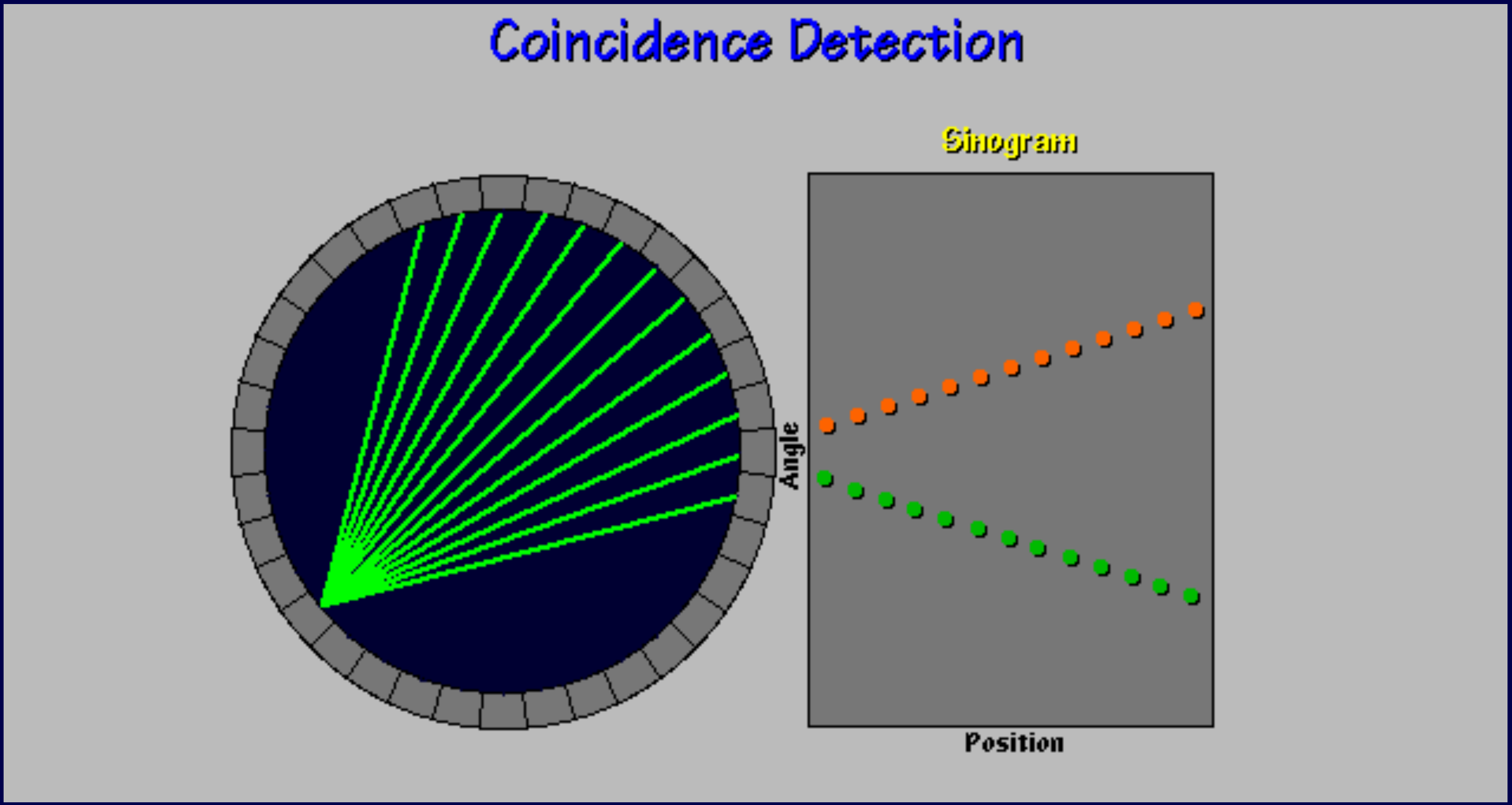
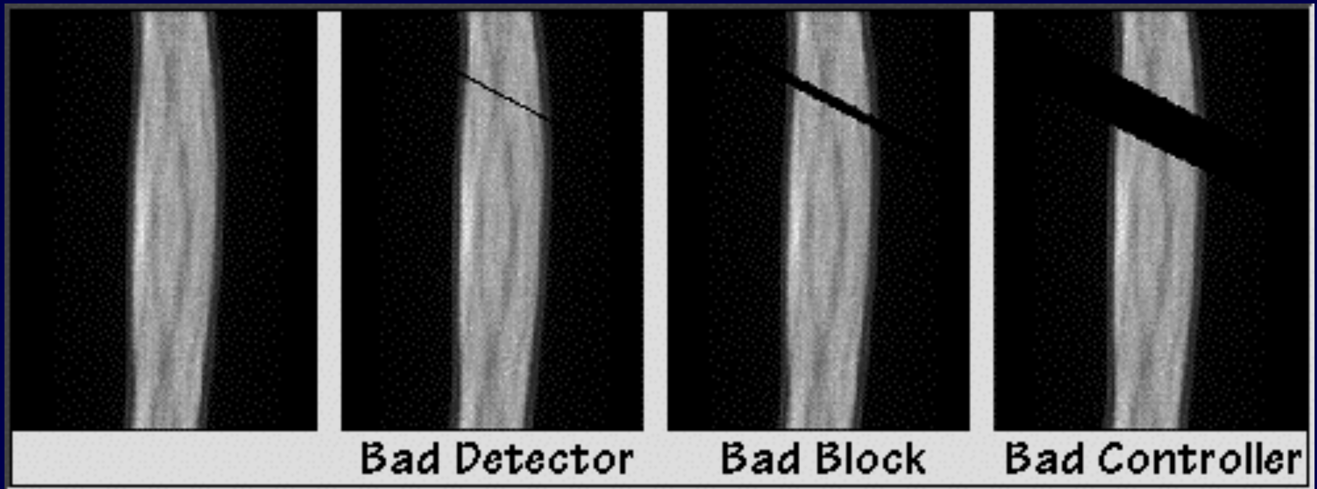


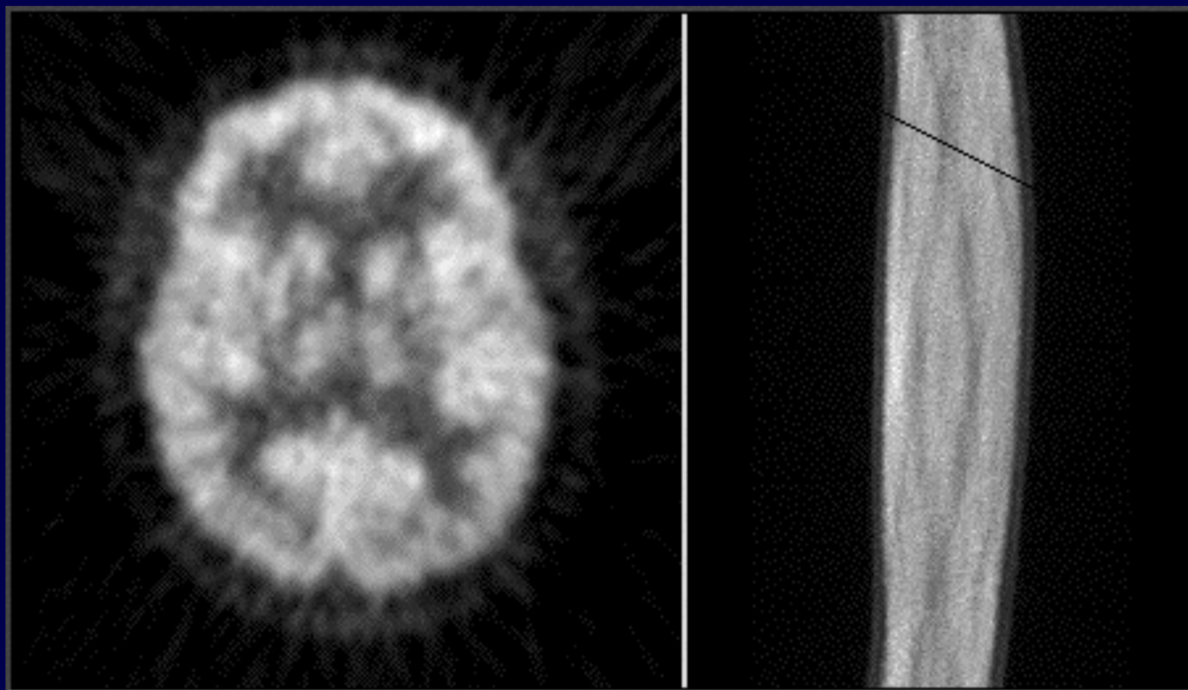






Courtesy, Crump Institute of Molecular Imaging, UCLA School of Medicine





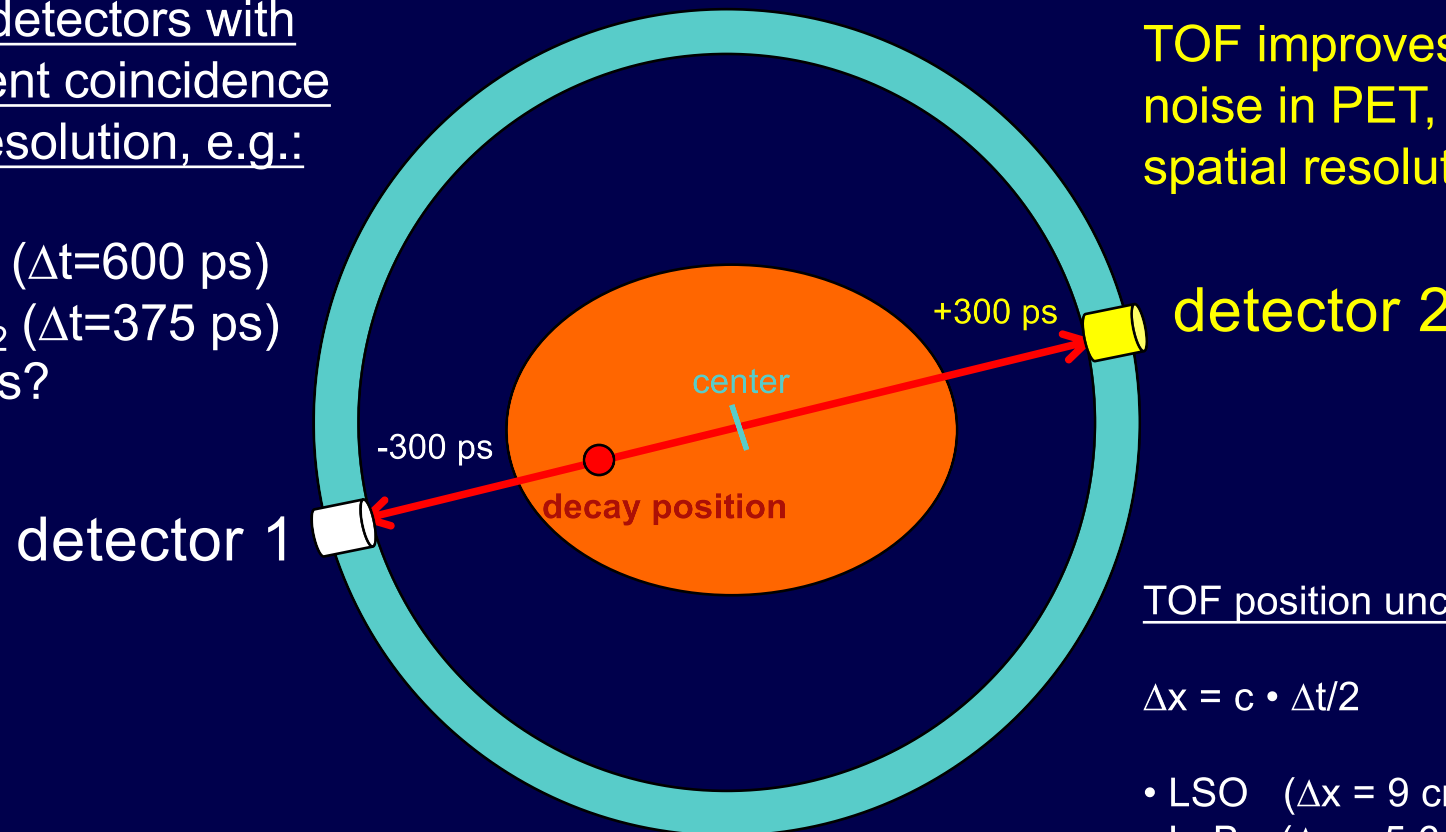
Courtesy, Crump Institute of Molecular Imaging, UCLA School of Medicine

Time-of-Flight (TOF) PET

Need detectors with excellent coincidence time resolution, e.g.:

- LSO (Δt=600 ps)
- $LaBr_2$ (Δt=375 ps)
- others?

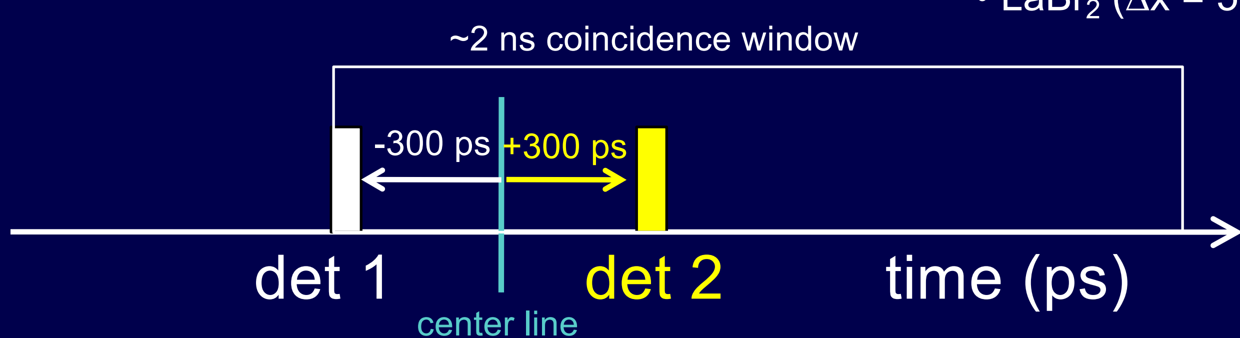
TOF improves image noise in PET, not spatial resolution!



TOF position uncertainty:

$\Delta x = c \cdot \Delta t/2$

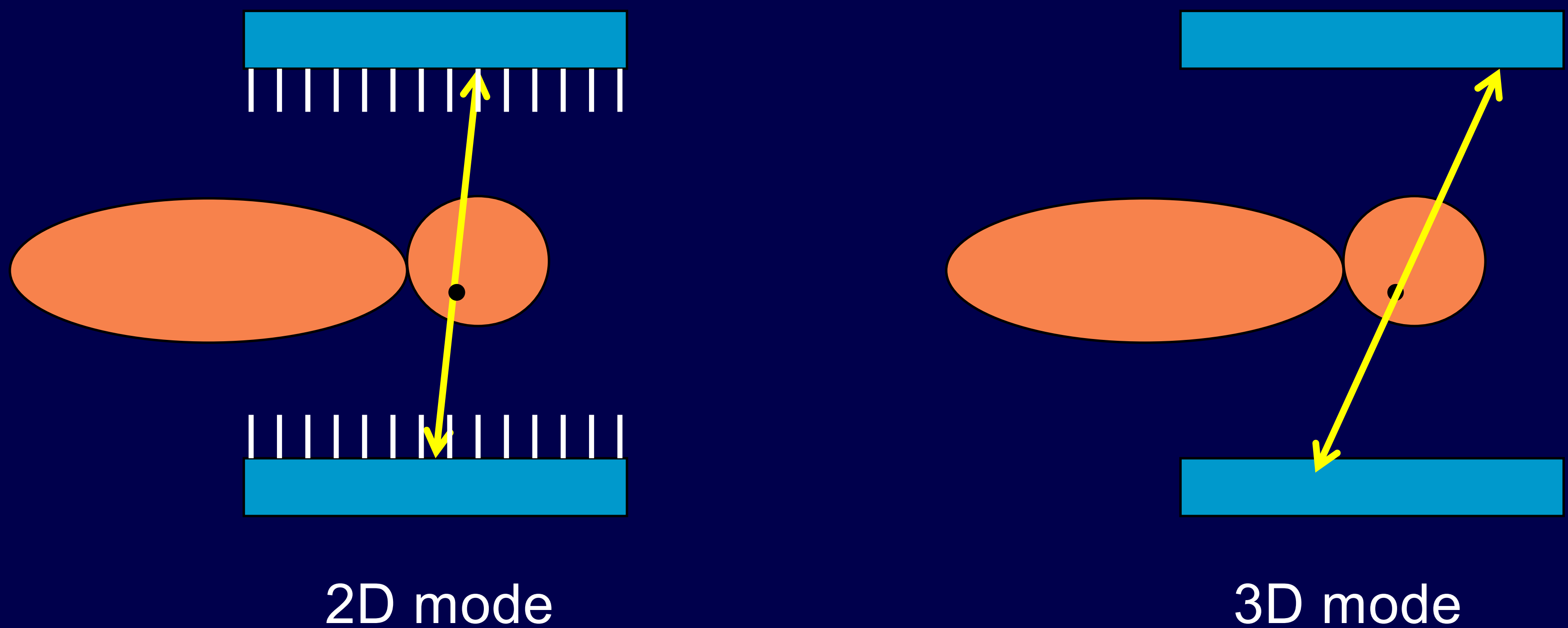
- LSO (Δx = 9 cm FWHM)
- $LaBr_2$ (Δx = 5.6 cm FWHM)



PET-CT Systems

- CT scan and PET scan are asynchronous but well registered spatially
- CT image is used for PET corrections for photon attenuation and scatter
- CT image is also useful for localizing lesions or defects on PET image

Acquisition Modes



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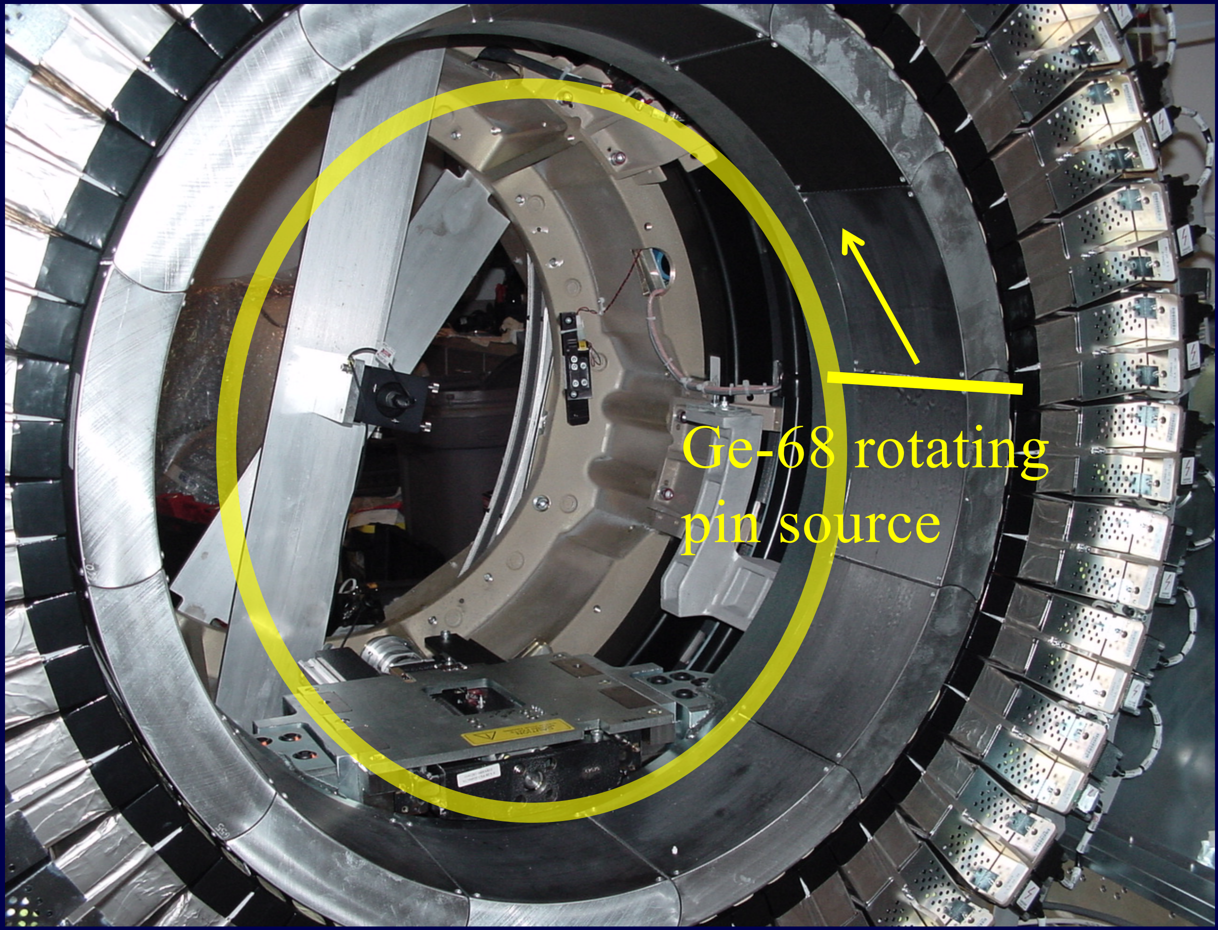
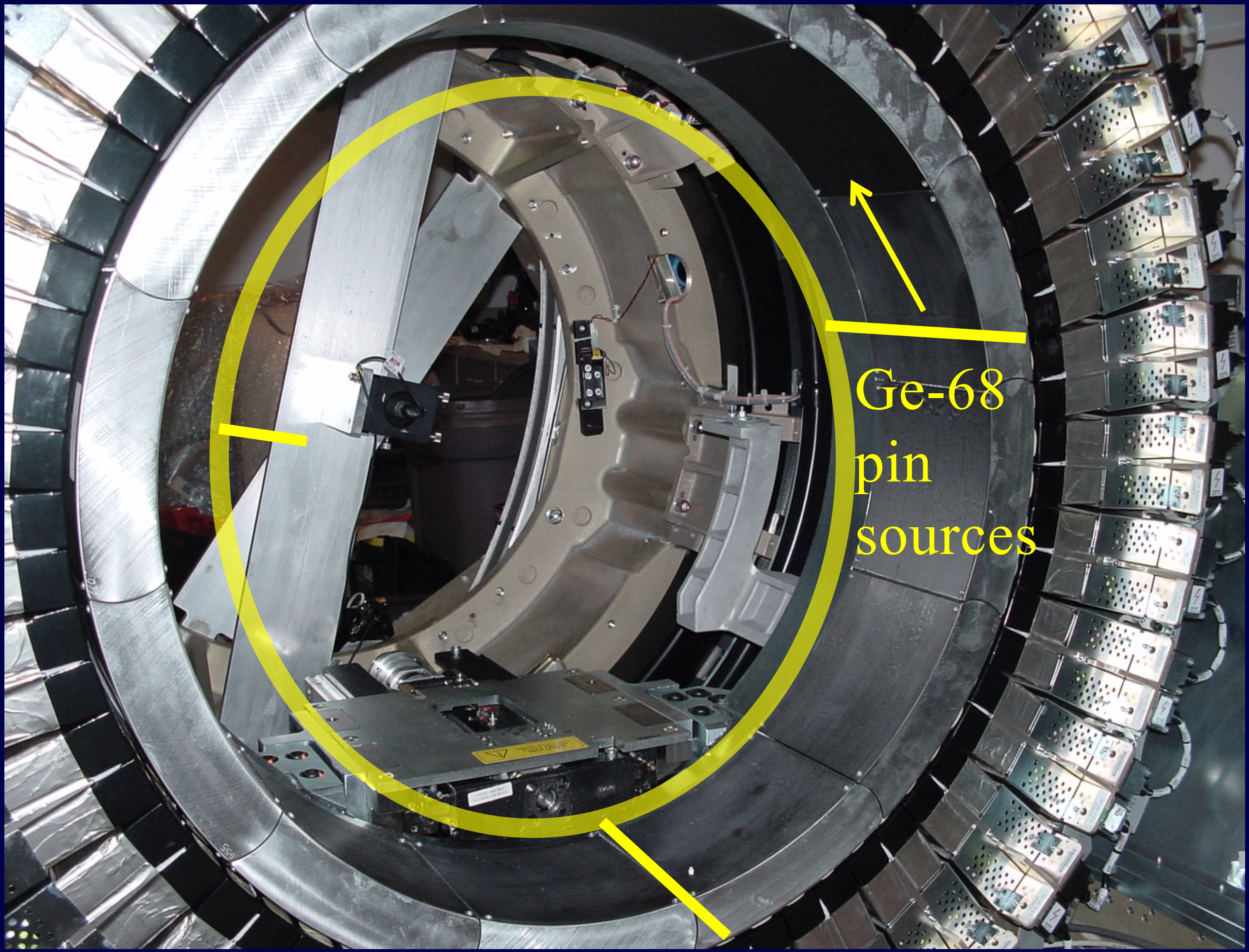
Quality Control: Detector Normalization



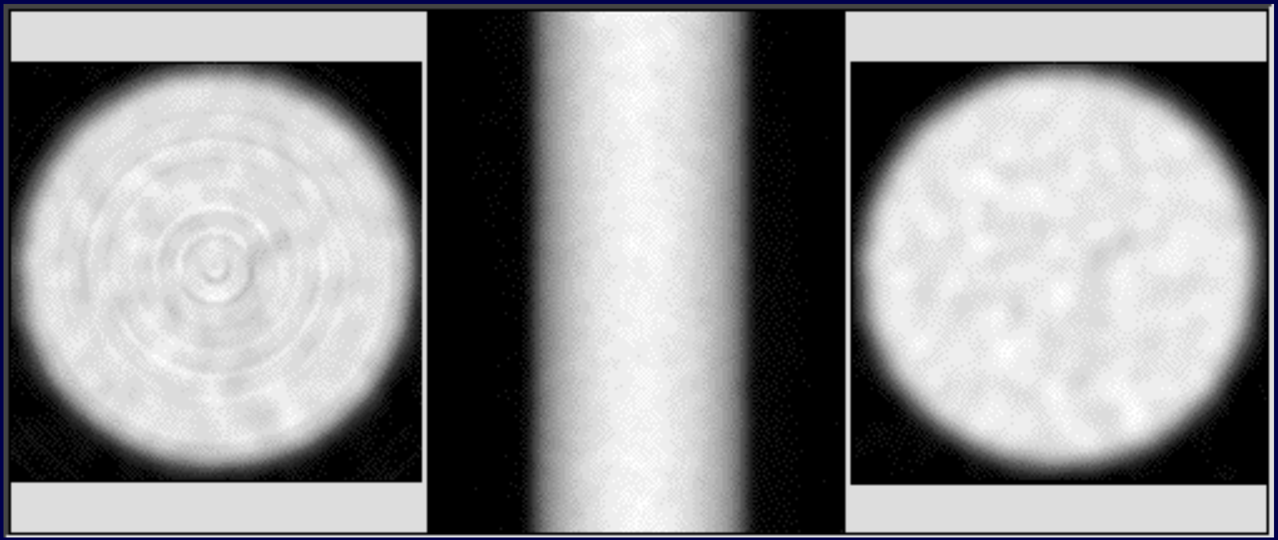
• Acquire coincidence data from rotating Ge-68 pin source for ≥ 12 hours
• Compute detector normalization (coincidence efficiency) corrections for all detector pairs

Quality Control: Blank Scan



- Blank scans are acquired on standalone PET scanners (with no CT scanner)
- Acquire an “air” scan using rotating Ge-68 pin source(s)
- Used for checking detectors each day of use, and could also be used for normalizing transmission scans of the patient to obtain an attenuation map.
- Note: a similar blank scan is also acquired on the CT scanner in PET-CT

Quality Control: Uniformity artifacts



failure in system processing hardware

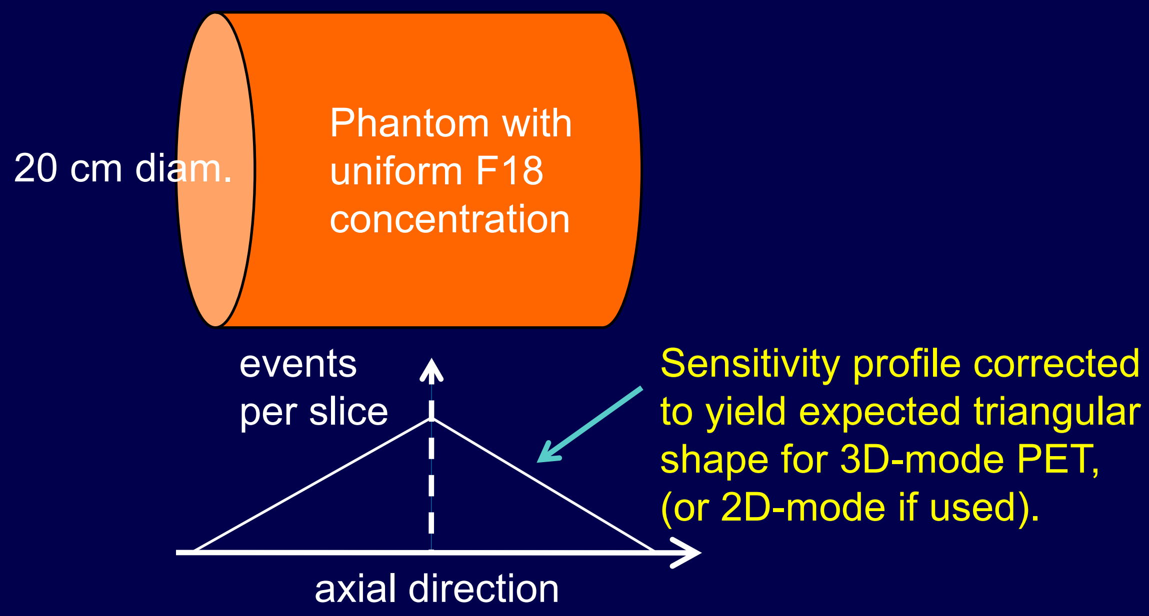
after repair of processing hardware

- Uniformity ring artifacts in PET are usually caused by a failure in the sinogram processing hardware, which handles all angular projections in the sinogram.

- Note that these types of artifacts could not be caused by a bad detector block, which would produce fan-shaped streak artifacts.

Courtesy, Crump Institute of Molecular Imaging, UCLA School of Medicine

Quality Control: PET phantom and well-counter SUV calibration



- Activity injected into phantom should be assayed in the same dose calibrator used for measuring patient doses.
- Liquid volume in phantom should also be known; hence, activity concentration is known.
- Phantom data are then used to correct for axial-slice sensitivity variation, as well as to convert counts / voxel to activity concentration (Bq per mL).
- Final check: SUV measured in phantom should be ~ 1.0 (e.g., 0.95 -> 1.05)

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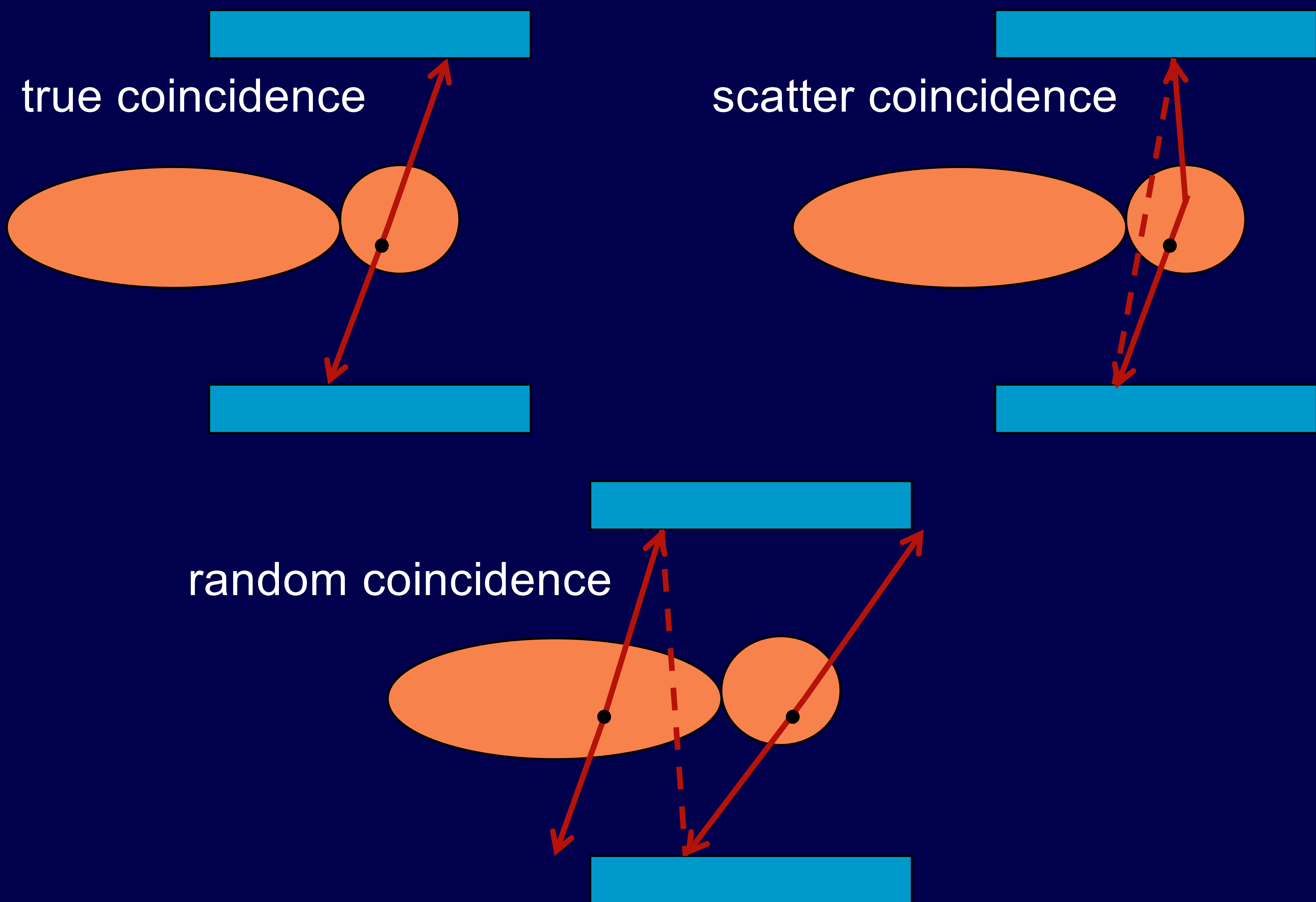
Event Types


true coincidence
scatter coincidence
random coincidence

Correction Methods for Random Coincidences

1. Use a delayed coincidence window to estimate random-coincidence counts in sinograms. Delay time must be long enough that true coincidences would all be excluded.

   • accurate, but noisy estimates of random count rates

2. Estimate randoms contribution to each sinogram bin using the rates of single photons hitting both detectors in coincidence:

$$R_{1,2} = 2\,\tau\, S_1\, S_2$$

$R_{1,2}$ = random coincidence estimate for detector pair (1,2)
τ = width of coincidence time window
$S_{1\,(2)}$ = singles count rate of detector 1 (2)

   • fairly accurate, low-noise random-coincidence estimates

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Correction for Scatter Coincidence Events

- For 2D PET, scatter can be modeled as the convolution of a scatter blurring function with the source distribution

- For 3D PET, use model-based "simulation"*. Define many possible "scatter points" inside the patient boundary (obtained from the attenuation map)

- Loop over all emission voxels, calculating the probability of Compton scatter from each scatter point to all possible detectors; this method models only <u>single</u> Compton scatters

- To estimate the <u>total</u> scatter, scale up the single-scatter distribution using coincidence lines of response outside the patient habitus so that they match the measured coincidences that appear to come from outside the patient's body.

- Random and scatter estimates are then included in the forward-projection of the iterative OS-EM reconstruction algorithm

(* JM Ollinger *PMB* 1996; C Watson *IEEE-TNS,* 1996 and 2000)

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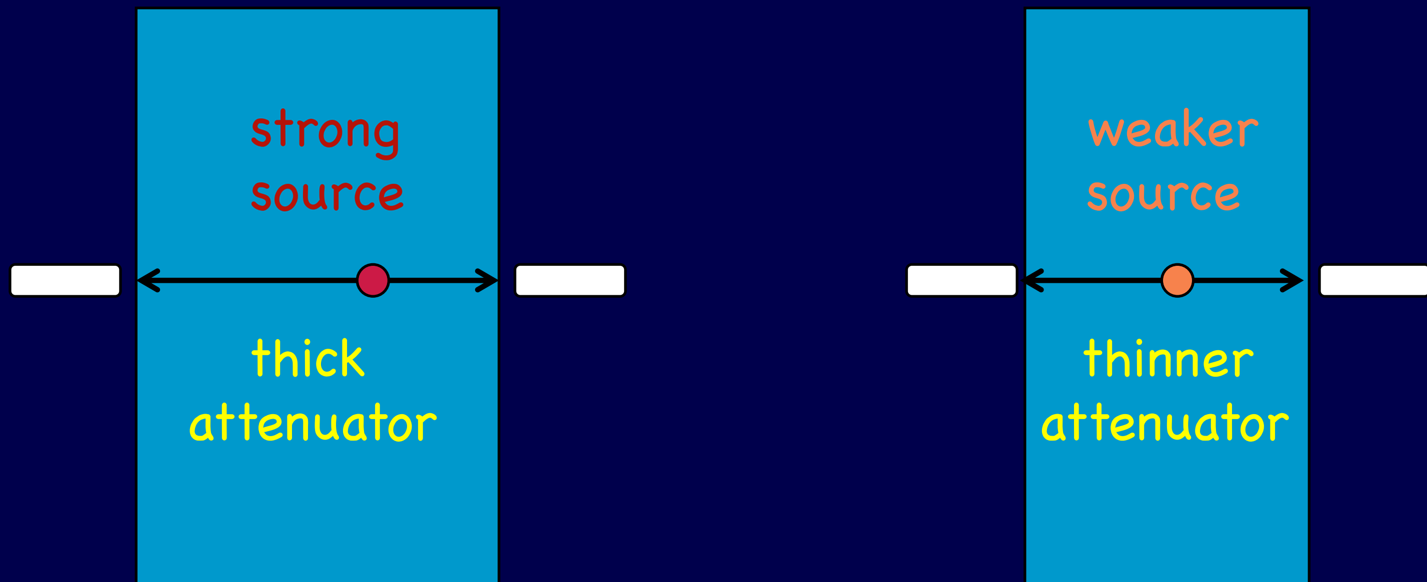
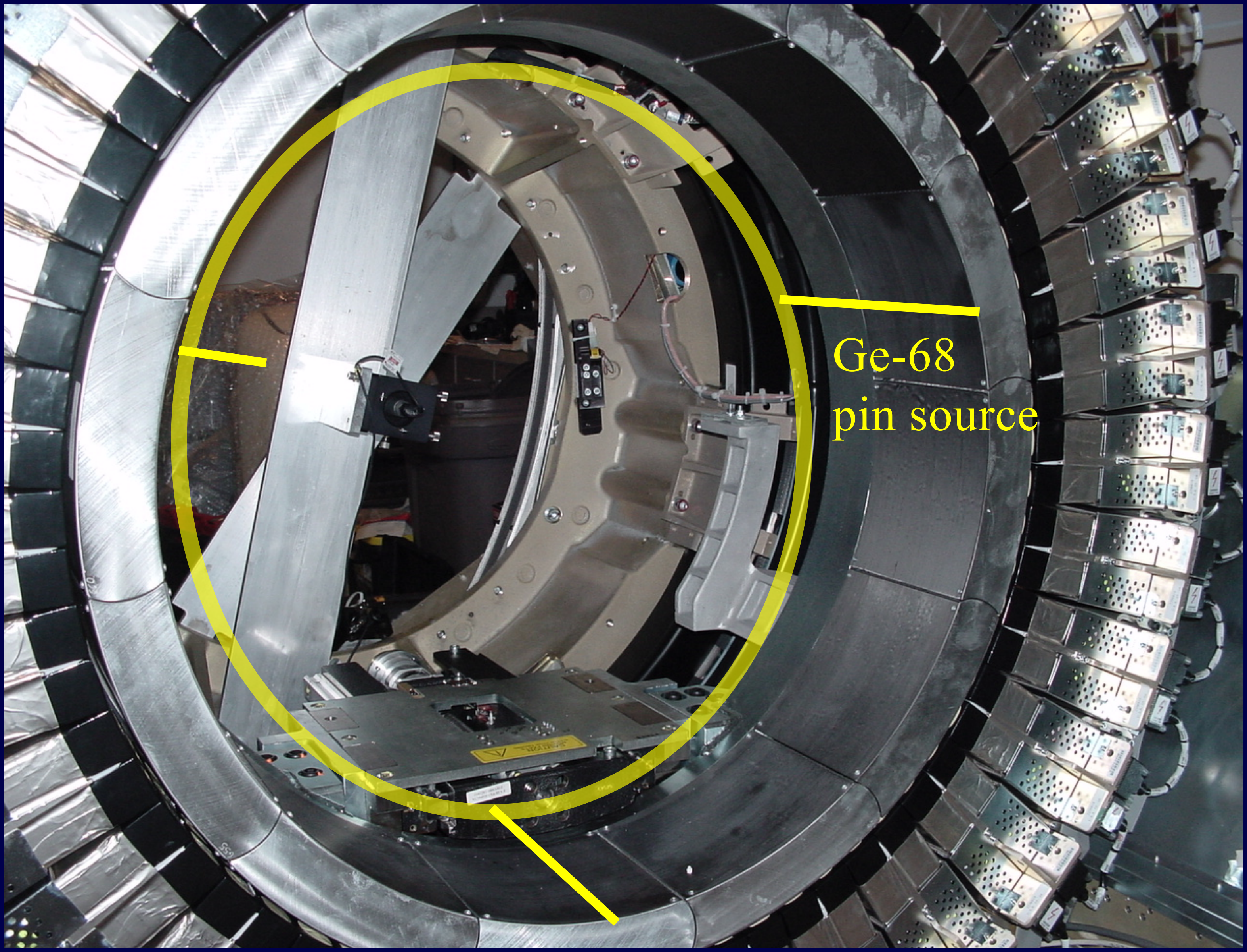
The Attenuation Problem in PET

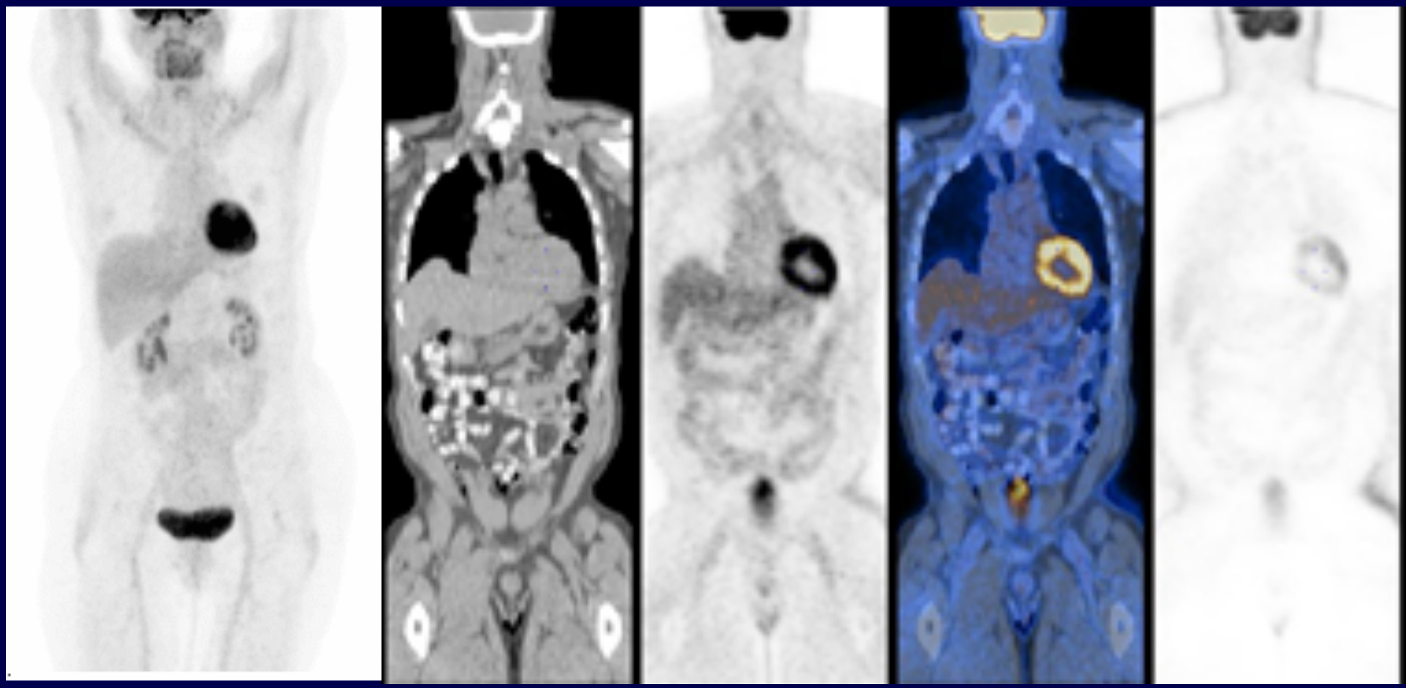
Fundamental ambiguity: same count-rate for



Can obtain attenuation map by Ge-68 transmission imaging:



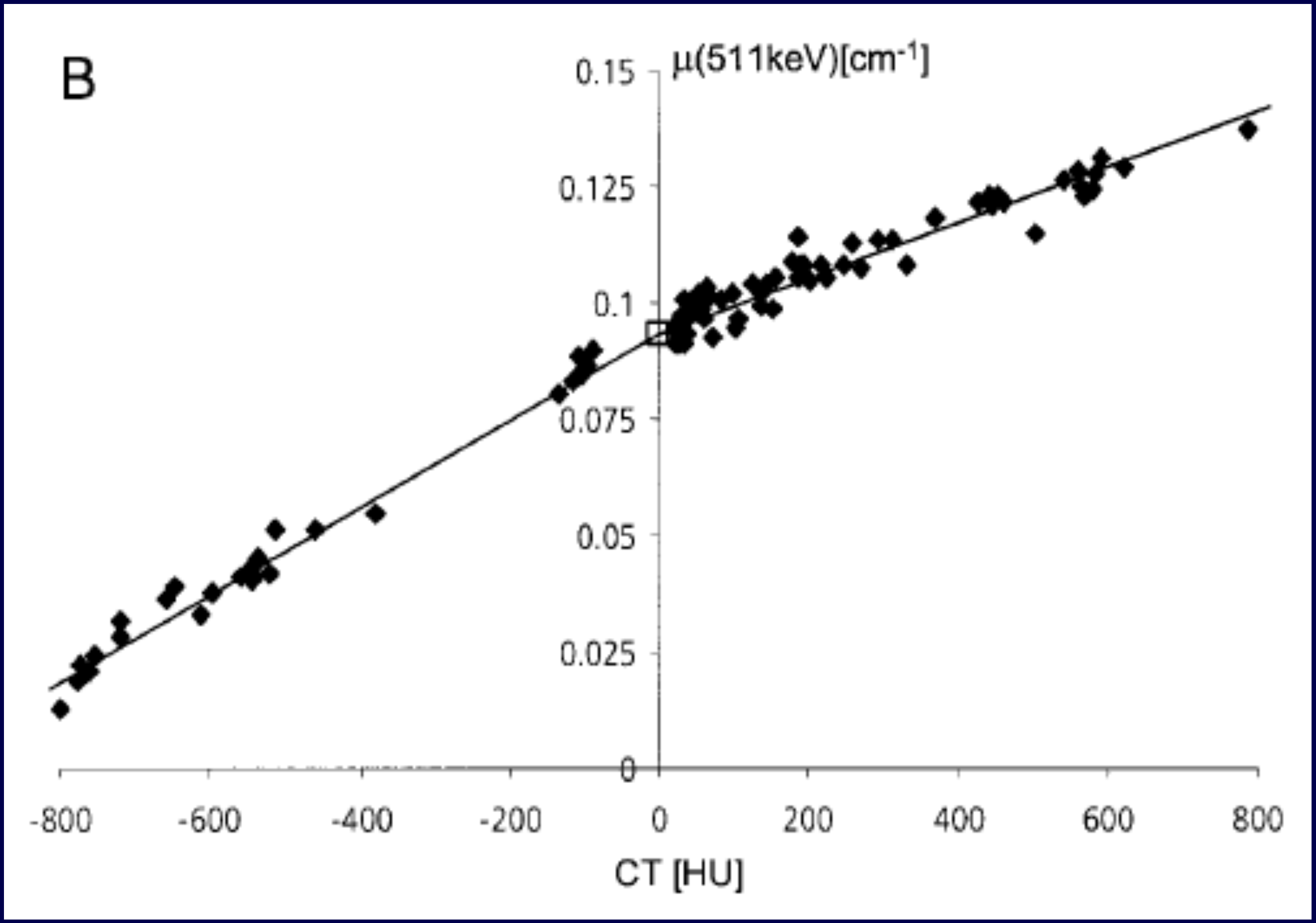
Typical image display screen for PET-CT imaging



C. Rajadhyaksha et al., JPNM teaching file

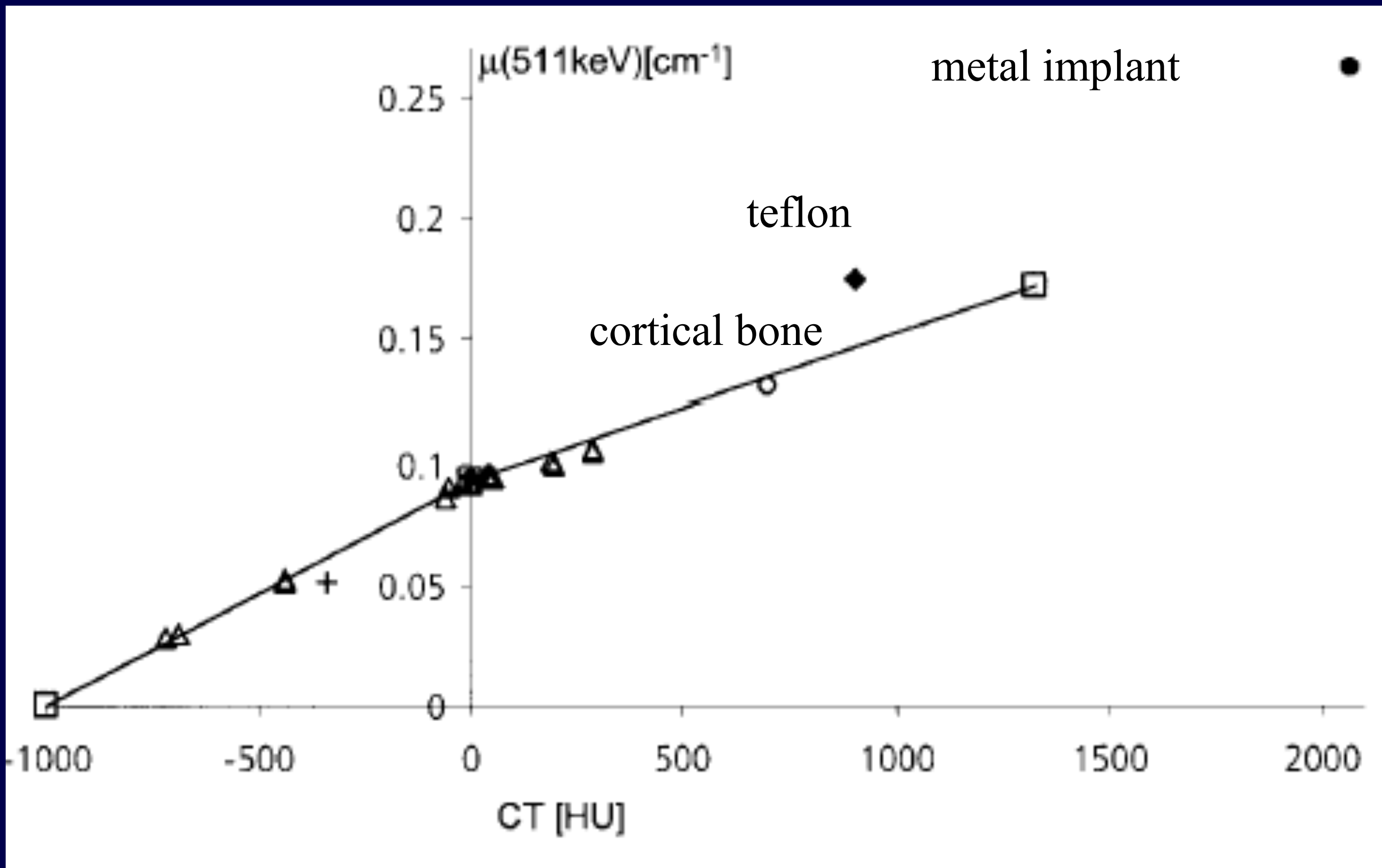
How to transform H.U. to μ-values

Data from 114 VOI drawn on images from 14 patients



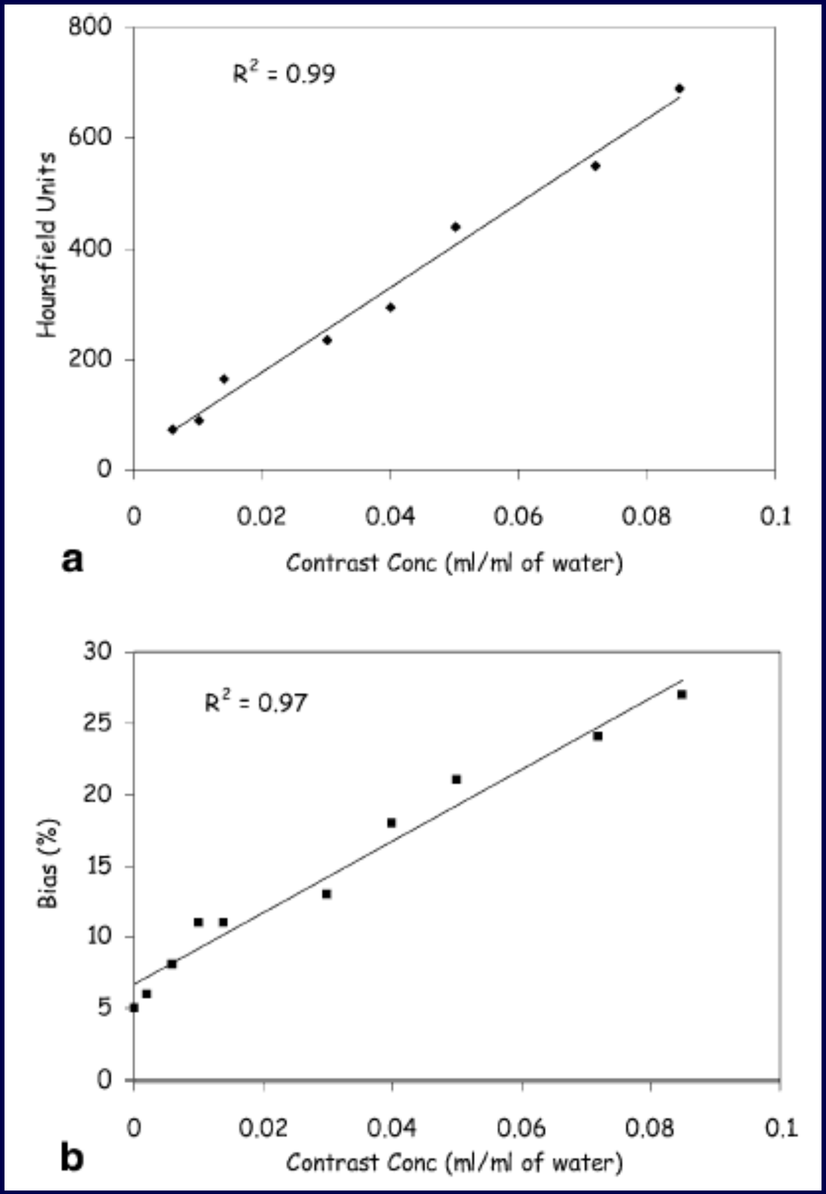
Burger et al., *Eur J. Nucl. Med.* (2002)29: 922-927.

Attenuation measurements of different materials



Burger et al., *Eur J. Nucl. Med.* (2002)29: 922-927.

Effect of iodinated contrast agent on PET accuracy

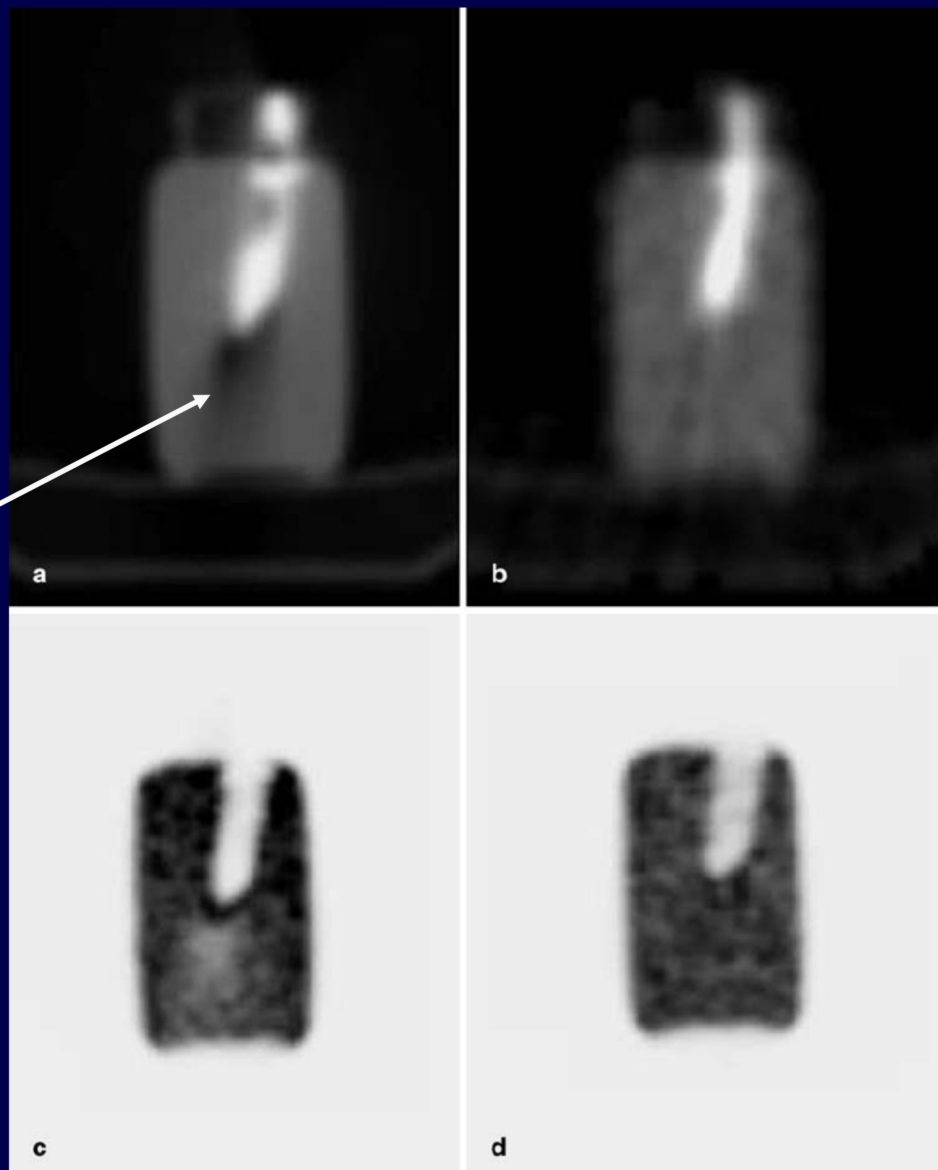


Visvikis et al., *Eur J. Nucl. Med.* (2003)30: 344-353.

Effect of a titanium implant

CT transverse slice

Ge-68 attenuation map

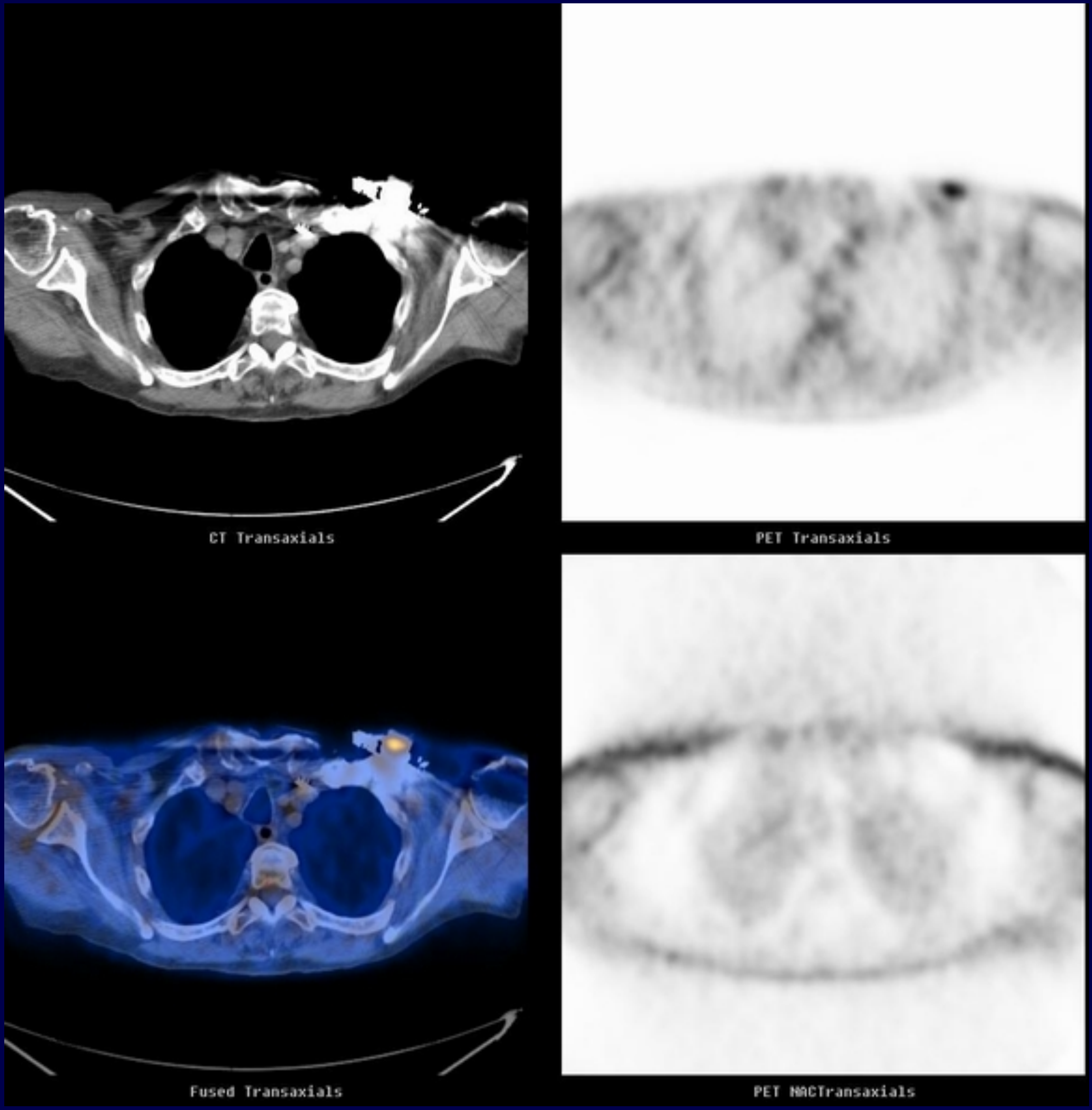


CTAC PET image

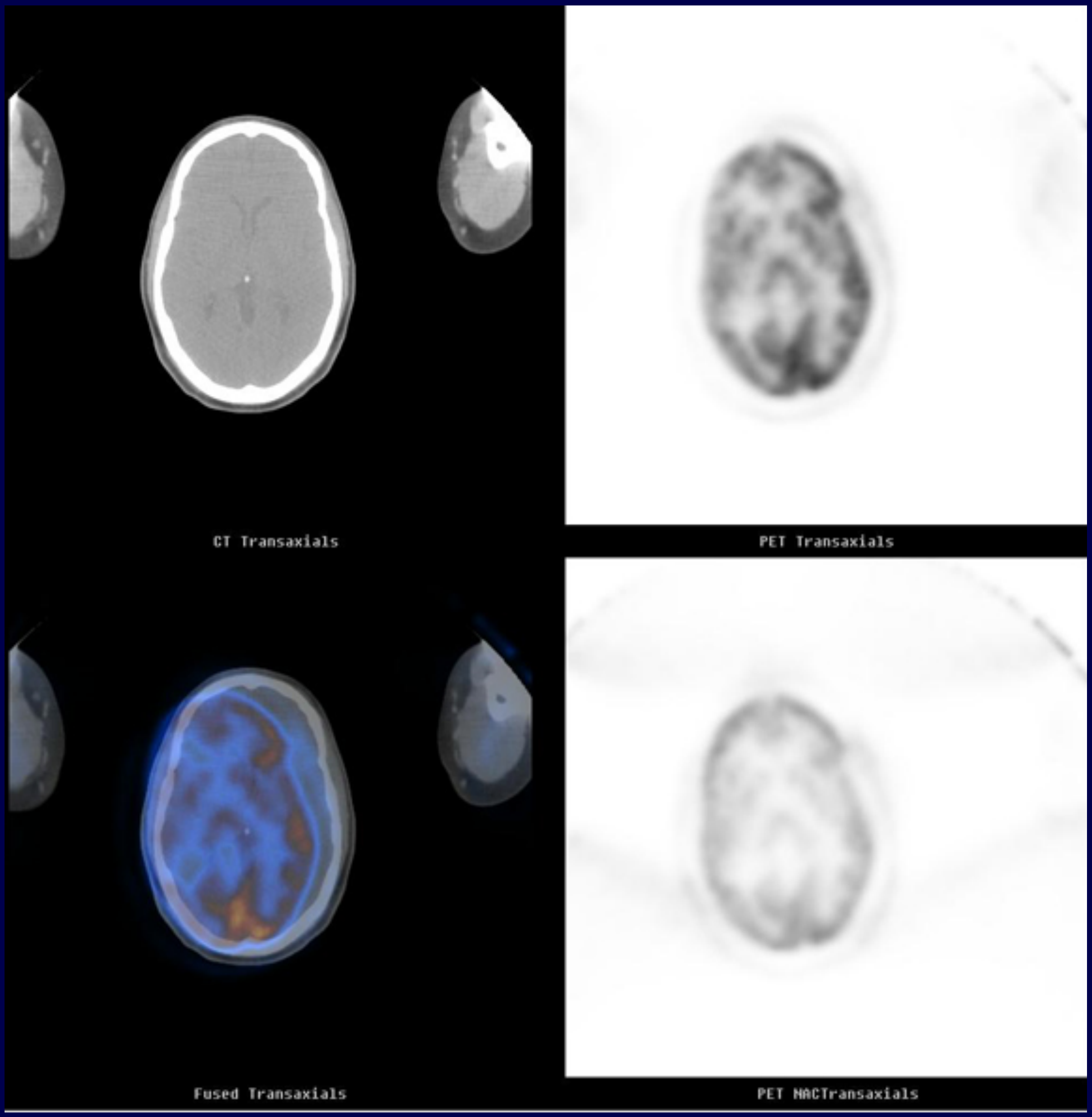
Ge-68-corrected PET image

Visvikis et al., *Eur J. Nucl. Med.* (2003)30: 344-353.

Pacemaker Artifact

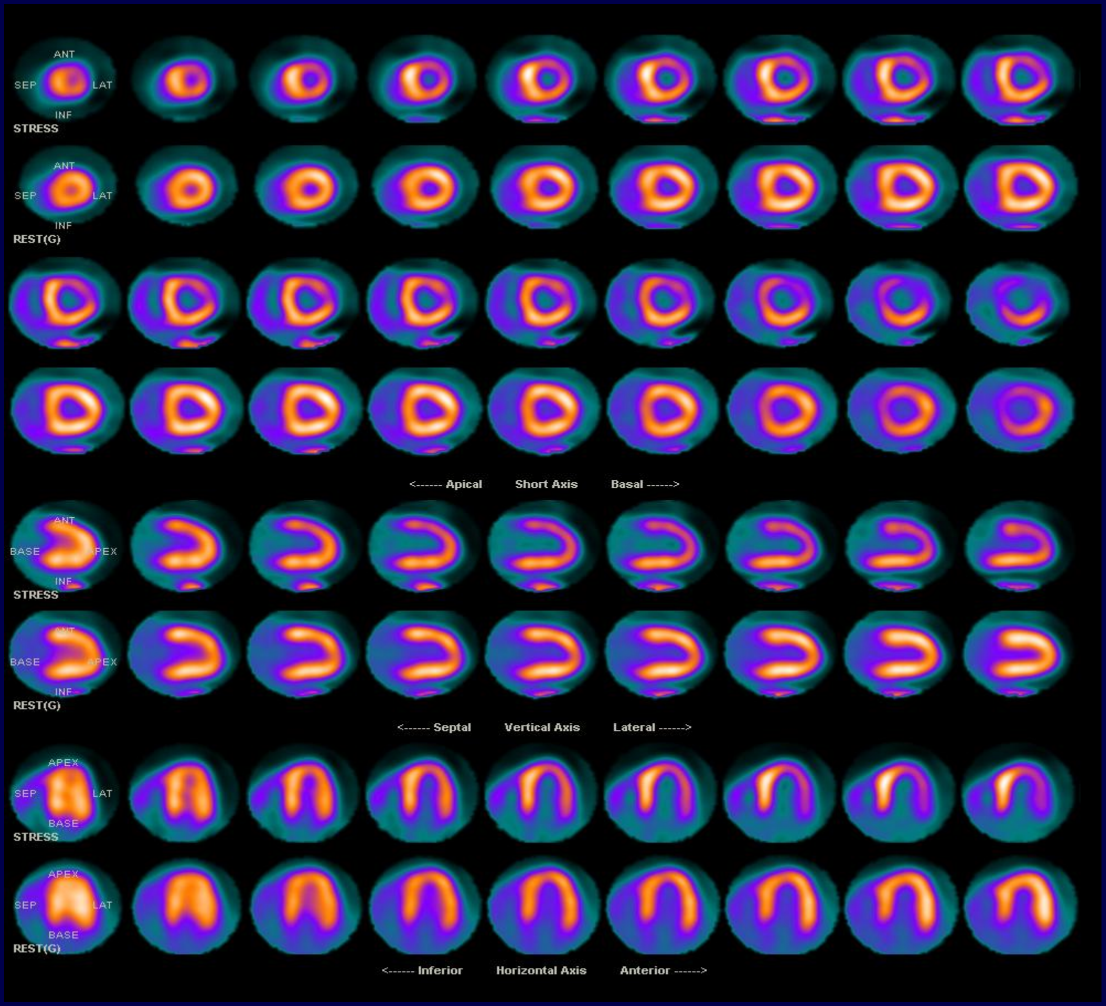


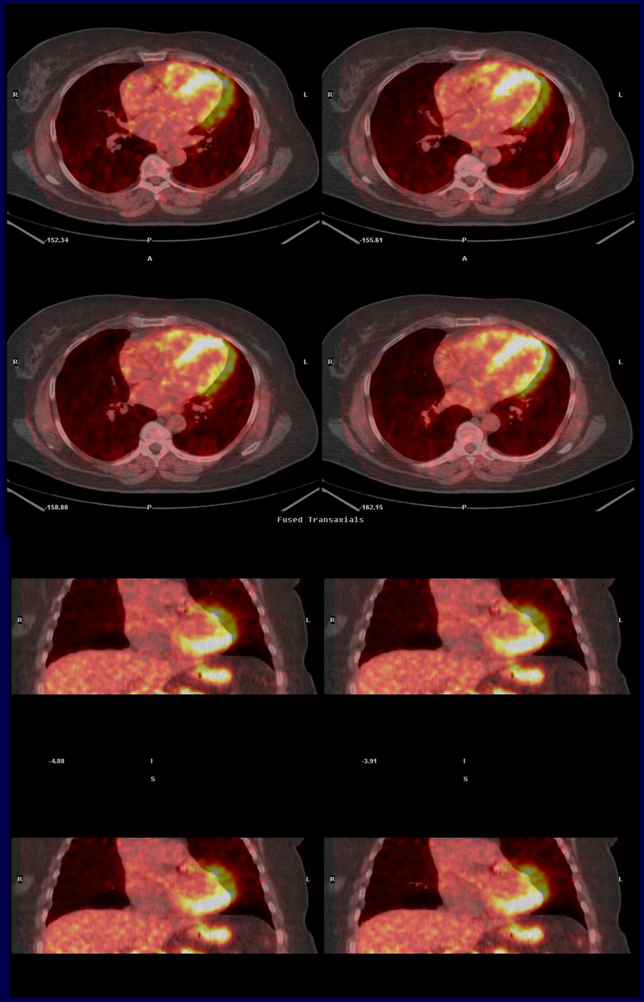
C. Rajadhyaksha et al., JPNM teaching file



C. Rajadhyaksha et al., JPNM teaching file

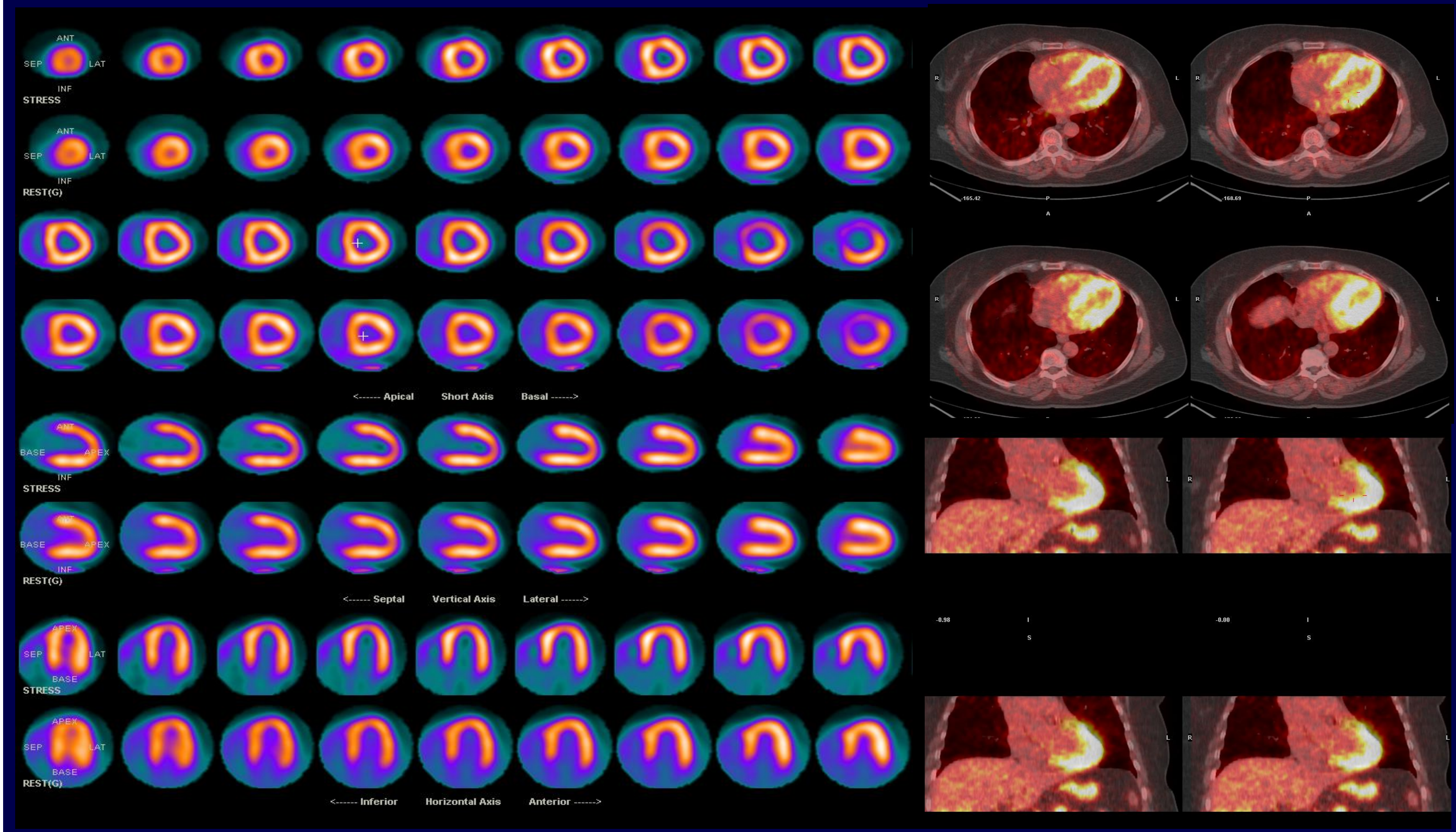
Emission-Transmission Registration





(from M. Di Carli, MD, 3/23/05)

Emission-Transmission Registration



(from M. Di Carli, MD, 3/23/05)

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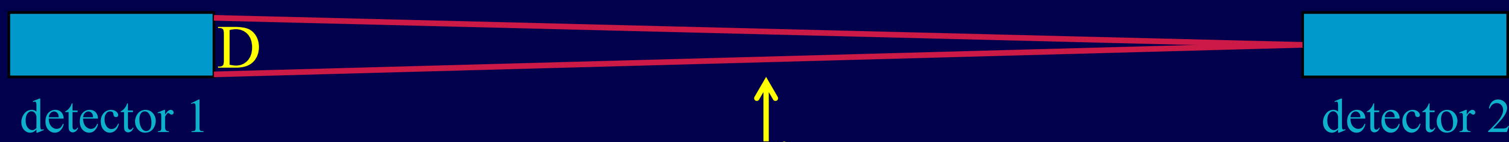
Factors affecting spatial resolution

1. Positron range (annihilation photons do not originate from the positron decay location):

   ~0.5 -> 2 mm, depends on energy and tissue density

2. Detector resolution:



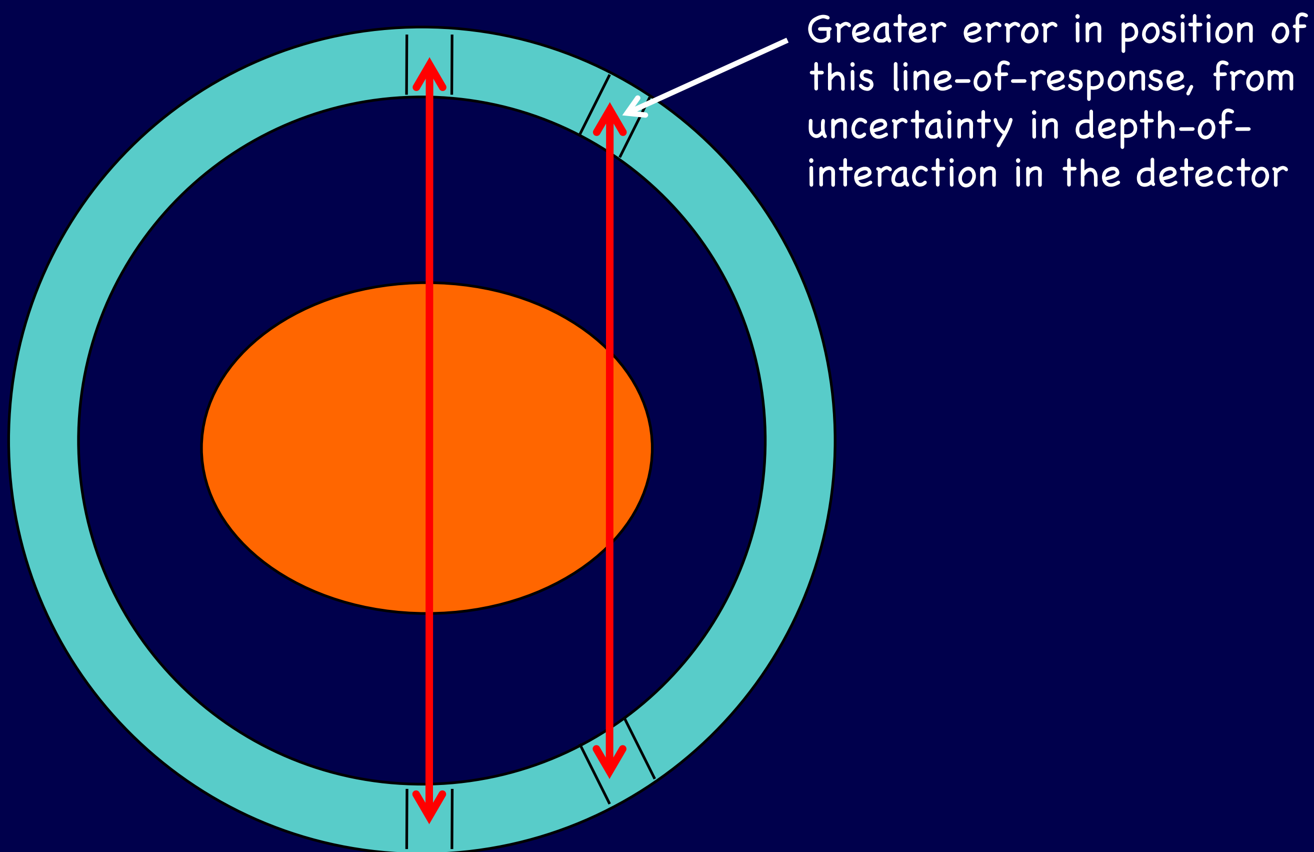
Res_{det} ~ D/2 = 3 mm

3. Non-colinearity of annihilation photons:

Res_{180} ~ 1.8 mm

Res. combined = $\{1^2 + 3^2 + 1.8^2\}^{1/2}$ = 3.6mm

Nonstationary spatial resolution



How to reduce resolution blurring:

- use dual detector rings to obtain better estimate of depth of interaction
- include a mathematical model of resolution blurring in the forward projector used to estimate projections within an OS-EM reconstruction.

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Standardized Uptake Values (SUV)
(or Silly Useless Values)?

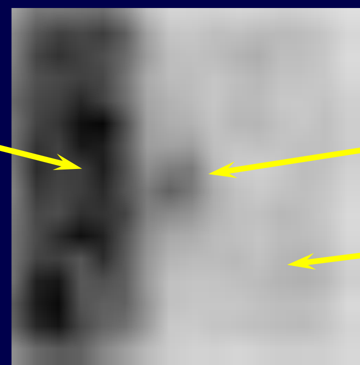
Definition of SUV:

$$\text{SUV} = \frac{\text{activity concentration measured in tissue VOI (Bq/ml)}}{\text{decay-corrected injected activity concentration (Bq/g)}}$$

NOTE: There are several variants, e.g., SUV-ave, SUV-max, etc. and several different suggested methods for normalization.

SUV in small structures are inaccurate (partial volume effect)

16x16 image patch



liver is 5mm from tumor boundary

- counts from tumor are blurred into surrounding regions
- counts from lung and liver are blurred into tumor
- resolution (degree of blurring) depends on the location of the tumor in the PET scanner, and on the reconstruction method

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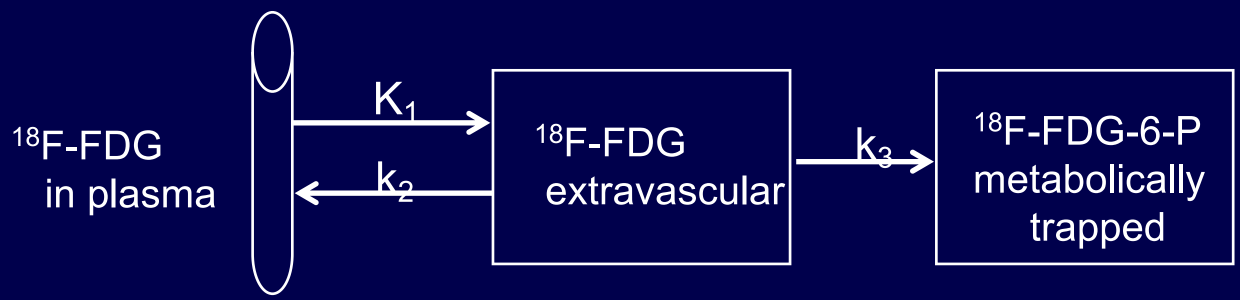
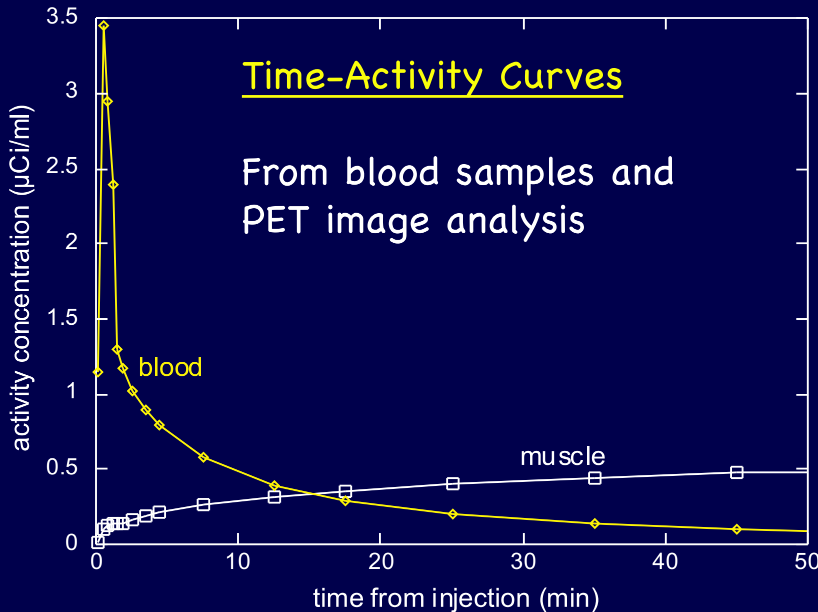
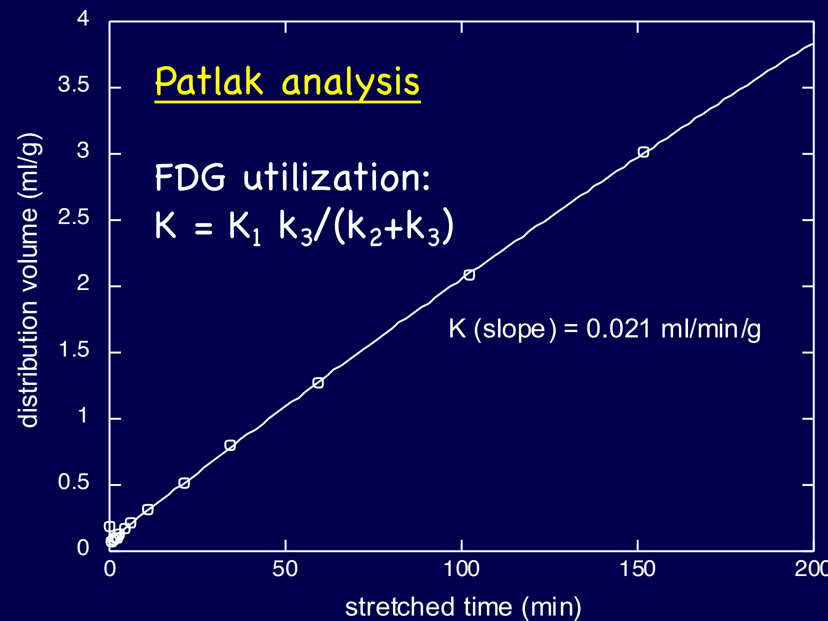
Tracer-kinetic modeling: Absolute quantification of blood flow or metabolism from dynamic PET image data



Example: Calf muscle utilization of glucose in Peripheral Arterial Disease (PAD)





(Collaboration with M. Creager and colleagues, Cardiovascular Medicine)

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Equipment QC Requirements for PET Accreditation

JCAHO (accreditation by ABR or ICANL should help with JCAHO)

1. Maintain service records signed by a qualified individual (service engineer) to indicate the equipment has been cleared for return to clinical use.
2. Must have written equipment QC plan in the Procedure Manual. Must include monitoring of instrument performance at least quarterly by a Medical Physicist or other qualified person.

ICANL (Intersocietal Commission for the Accreditation of Nuclear Laboratories)

1. Includes requirements above for JCAHO
2. Daily blank scan to check detectors
3. Cylinder phantom check of tomographic uniformity (per manufacturer's recommendation
4. Bed position alignment, if applicable for procedures performed (per manufacturer)
5. Detector normalization calibration (after hardware change, or per manufacturer)
6. Preventive maintenance of PET scanners at least every 6 months
7. Absolute activity calibration (after hardware change, or per manufacturer).
8. PET-CT spatial registration check (monthly, or per manufacturer).
9. Usual CT required tests, including annual tests by a medical physicist.

Equipment QC Requirements for PET Accreditation

ACR Requirements

1. Basically, same procedures for service and QC as required by JCAHO and ICANL.

In addition:

2. Acceptance testing must be performed on systems when they are installed.

3. An overall survey of PET performance should also be done at least annually thereafter.

- This should include standard QC tests, plus
- overall system performance with ACR-approved PET phantom
- system safety interlock checks
- in the future, full NEMA PET testing may be required