بسم الله الرحمن الرحيم

in the Name of Allah, the Beneficient, the Merciful

TEHRAN UNIVERSITY OF MEDICAL SCIENCES

Reconstruction of PET/CT images: Challenges and Opportunities

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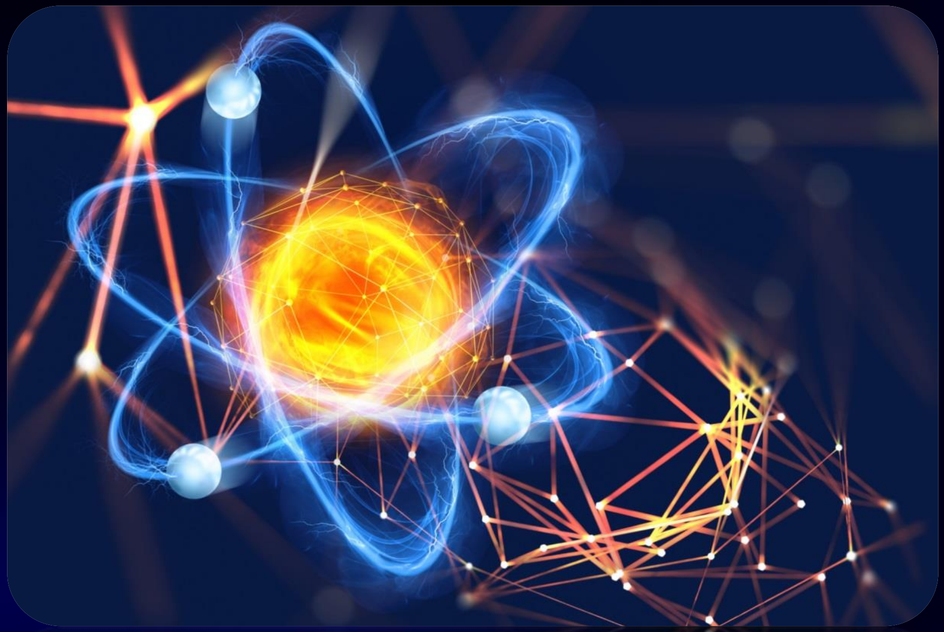
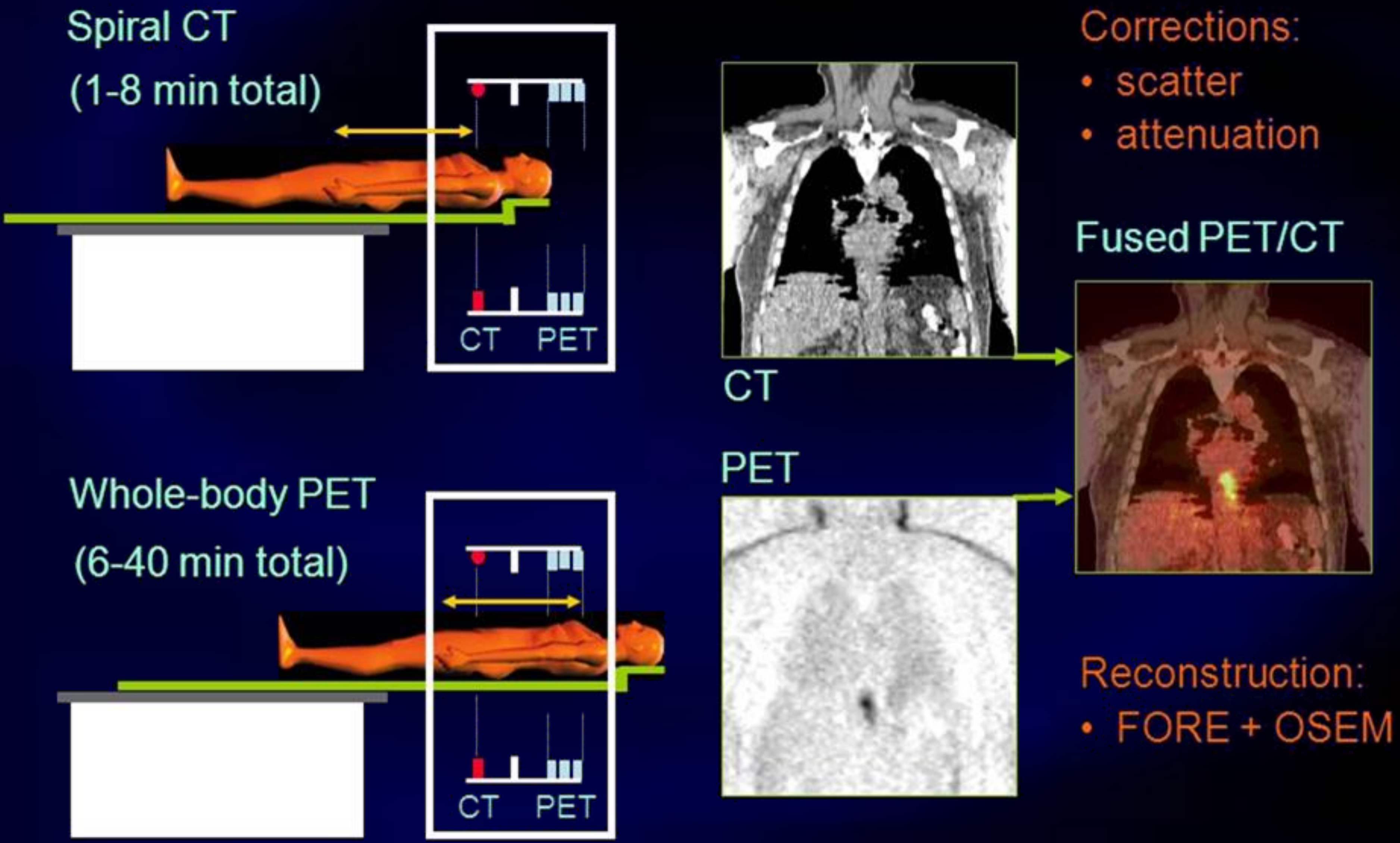
Outline

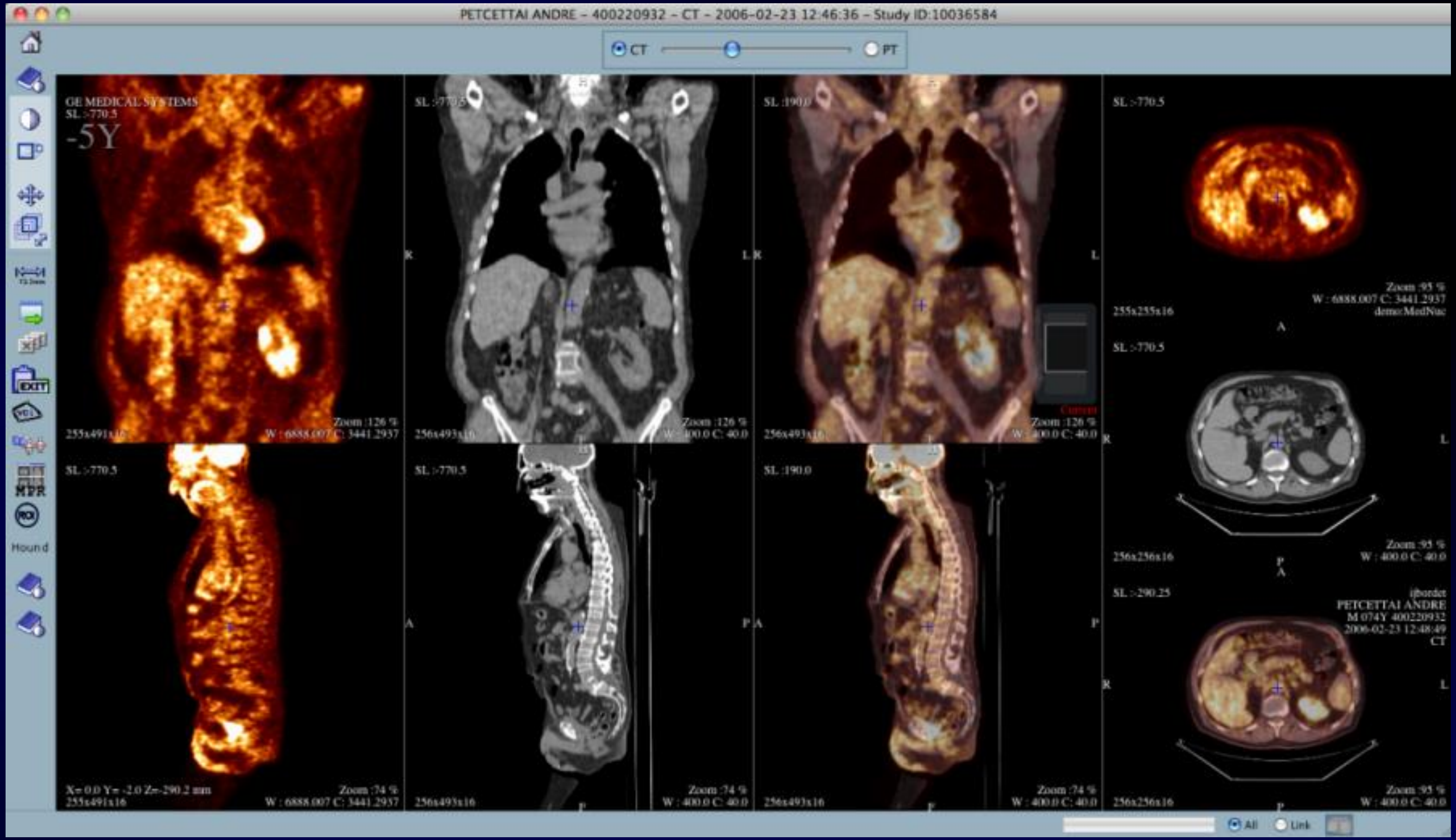
- Introduction
- Basic Concepts
- Data Correction
- Effects of Image Reconstruction Parameters on PET Images
- Commercial Options
- Challenging Area



Introduction

PET/CT imaging





- diagnosis
- staging / restaging
- therapy monitoring
- treatment planning in clinical oncology

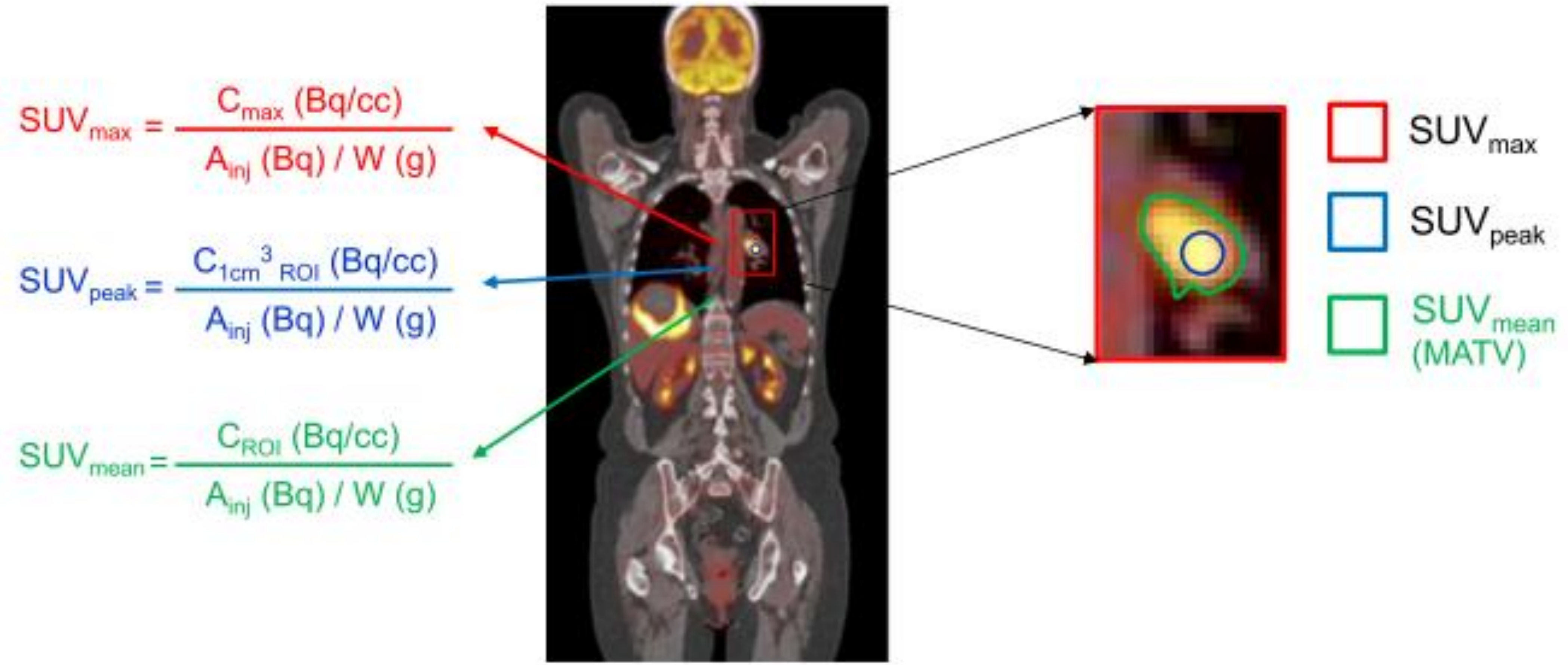
SUV

$$SUV = \frac{\text{Activity concentration in tissue}}{(\text{Injected activity})/(\text{Body size})}$$

BIOLOGICAL	
Element	**Description**
PVE	
Patient preparation	
Tumor heterogeneity	
Tumor size	*Including leakage from nearby structures.*
Cell type	
Tumor avidity	
Other phenotype information	
Treatment effectiveness	
Patient motion	*Between the PET and the CT scan.*
Respiratory motion	
True tracer uptake	
Chemotherapy	*Disturbed renal function from chemotherapy can reduce the FDG clearance.*
Overlap between malignant and benign diseases	*Difficulties in deciding the correct threshold.*
Body size measurement	
Mass correction	
Blood glucose level	

TECHNOLOGICAL	
Element	**Description**
PET scanner	*Malfunction and sensitivity.*
Reconstruction algorithm	
Filters	*Consider level of smoothing.*
Interobserver variability	
Scan duration	
Sinogram noise	
Image noise	*Consider the noise level as it is a cause of over half of all* SUV_{max} *variation.*
Measurement error	*Occurs in 30 % of* SUV_{max} *measurements.*
Correct data entry	*9 of 15 steps are constructed so that a technologist is required to measure, record and/or enter a value.*
Image reconstruction parameters	*Number of iterations when using IR, field of view (FOV), number of subsets, voxel dimension, certain scanner specific enhancements, detector modeling and TOF.*
Timing mismatch	*Between the scanner and the dose calibrator.*
SUV variability	*The variation is described to have a log-normal distribution rather than a normal distribution.*
Calibration errors	*According to the decay of the radio-pharmaceutical.*
Contrast material	

SUVs

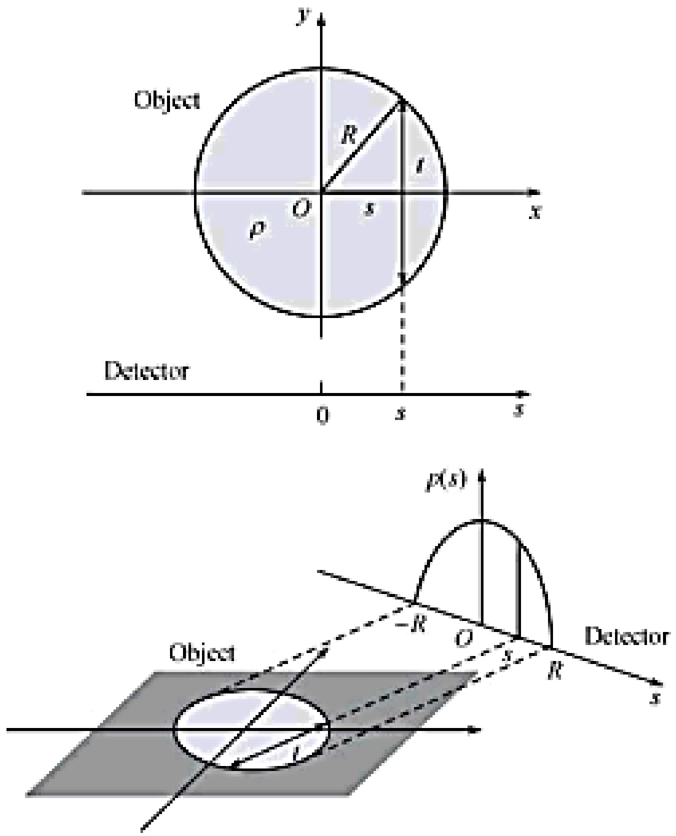


$SUV_{max} = \frac{C_{max}\ (Bq/cc)}{A_{inj}\ (Bq)\ /\ W\ (g)}$
$SUV_{peak} = \frac{C_{1cm^3\ ROI}\ (Bq/cc)}{A_{inj}\ (Bq)\ /\ W\ (g)}$
$SUV_{mean} = \frac{C_{ROI}\ (Bq/cc)}{A_{inj}\ (Bq)\ /\ W\ (g)}$
SUV_{max}
SUV_{peak}
SUV_{mean} (MATV)

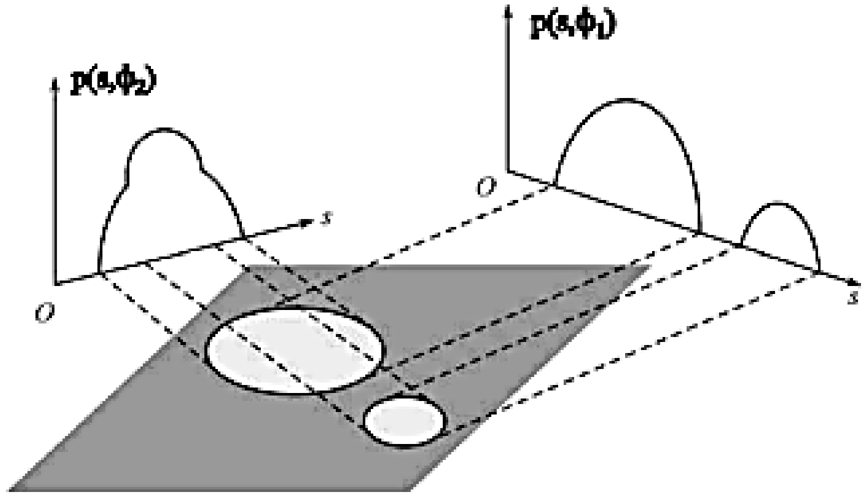
Basic Concepts

Image reconstruction

- Projection $p(s, \phi)$ at angle ϕ, s is coordinate on detector

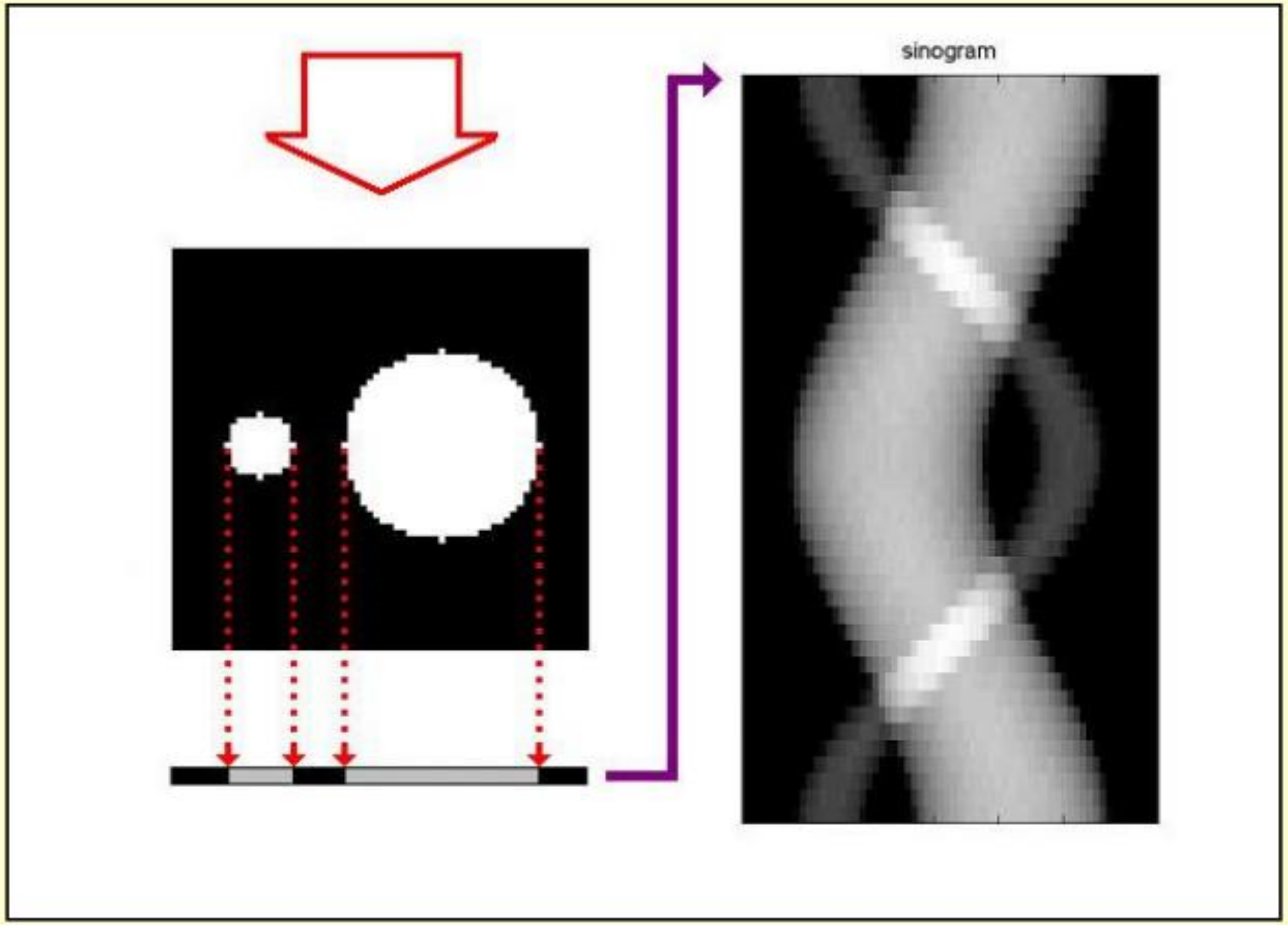


Projection $p(s)$ the same for any ϕ



Projection $p(s, \phi)$ depends on orientation

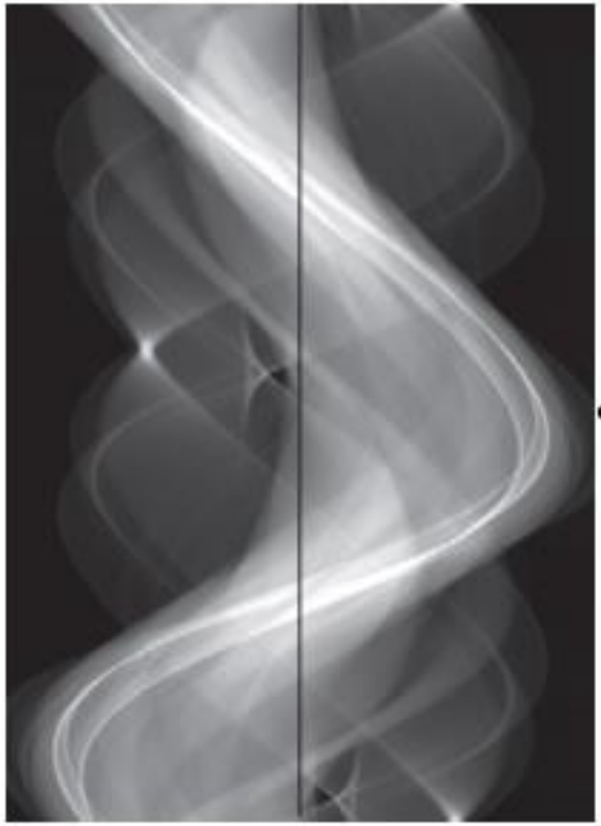
Sinogram = collection of projections of a single slice



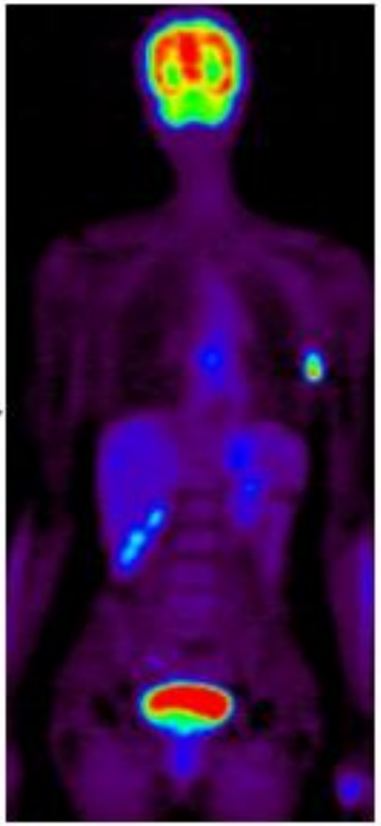
Tomography

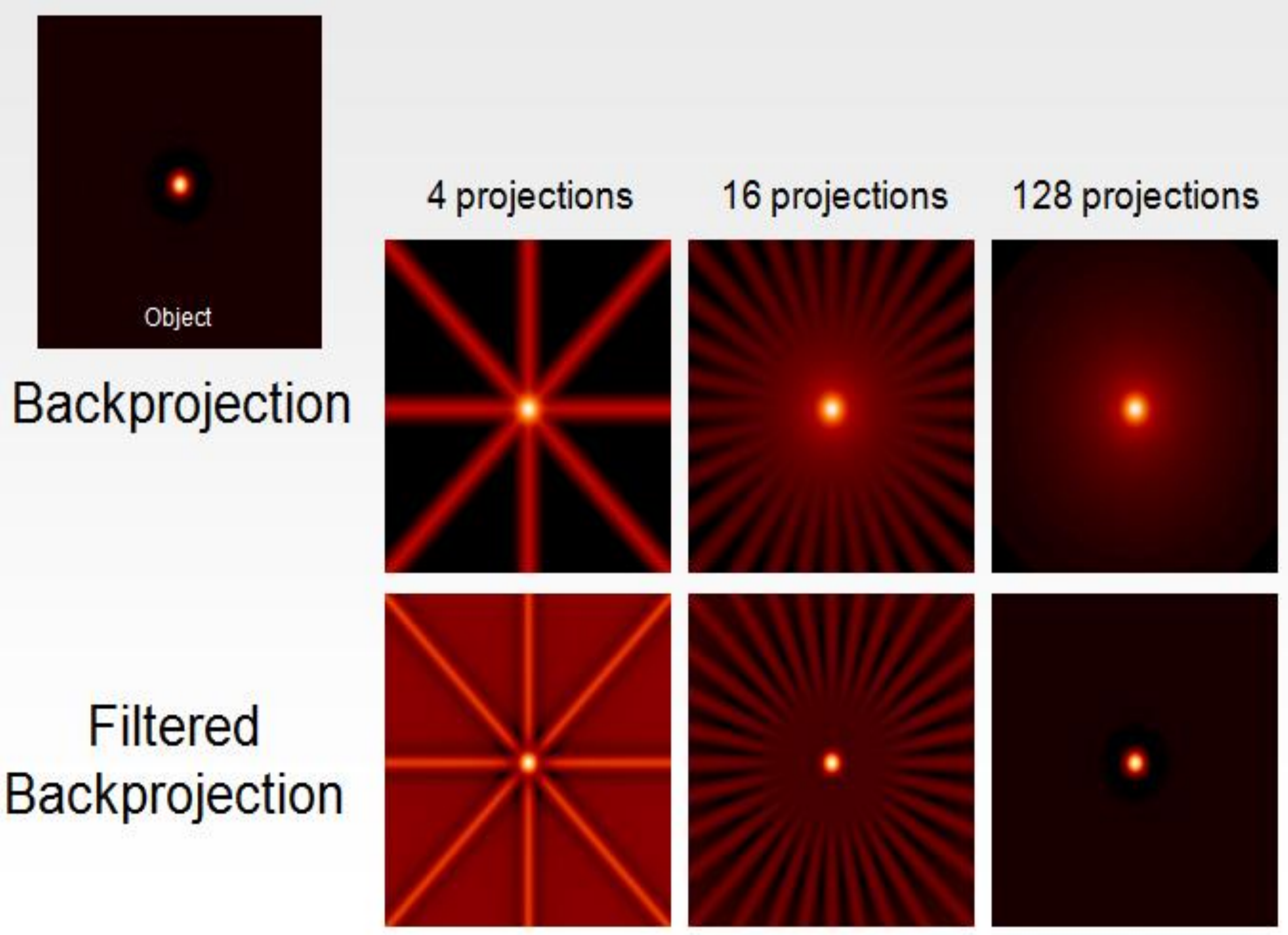
Find the image $f(x, y)$ from the measured projections $p(s, \phi)$

We measure a sinogram:



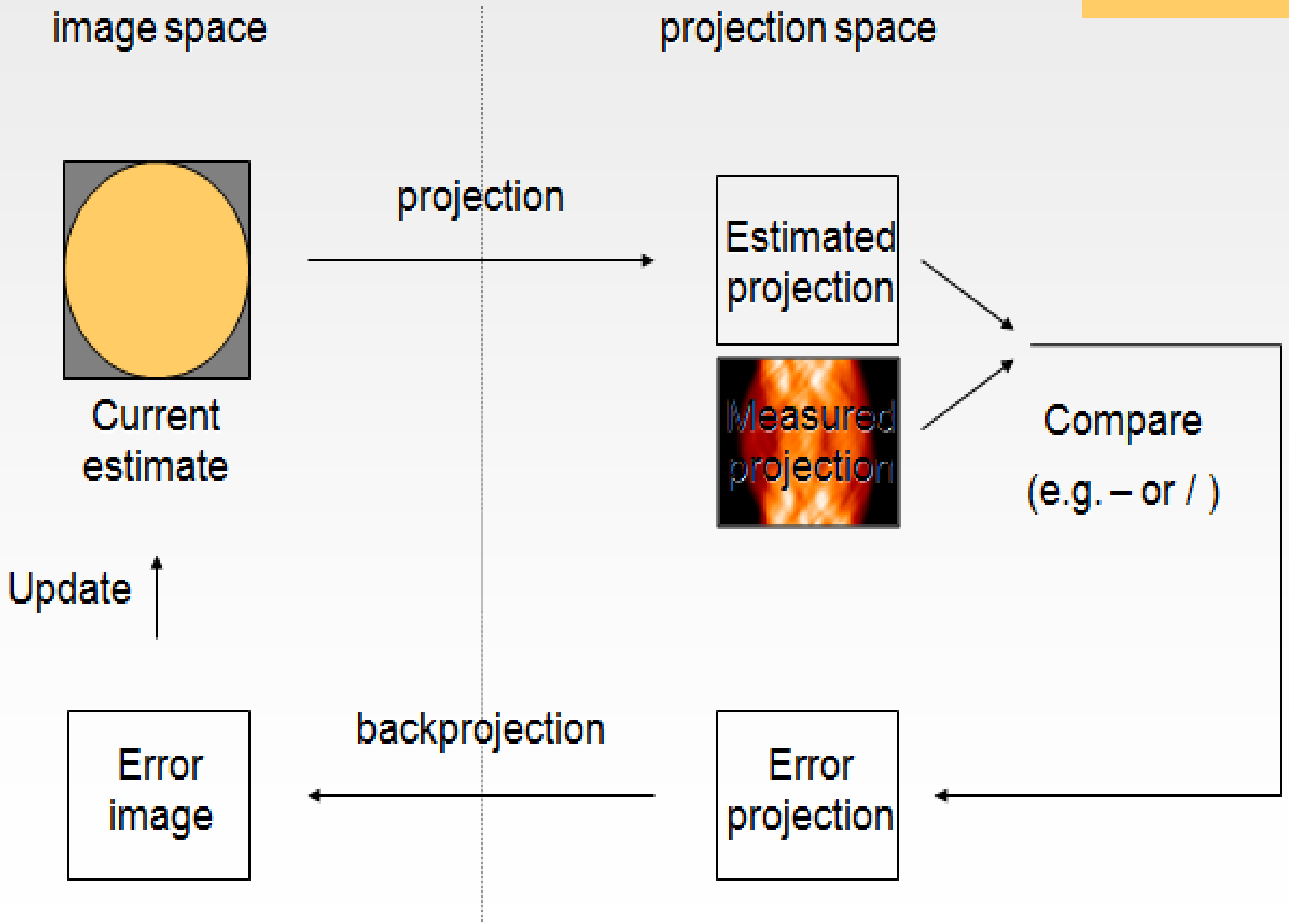
We want an image:



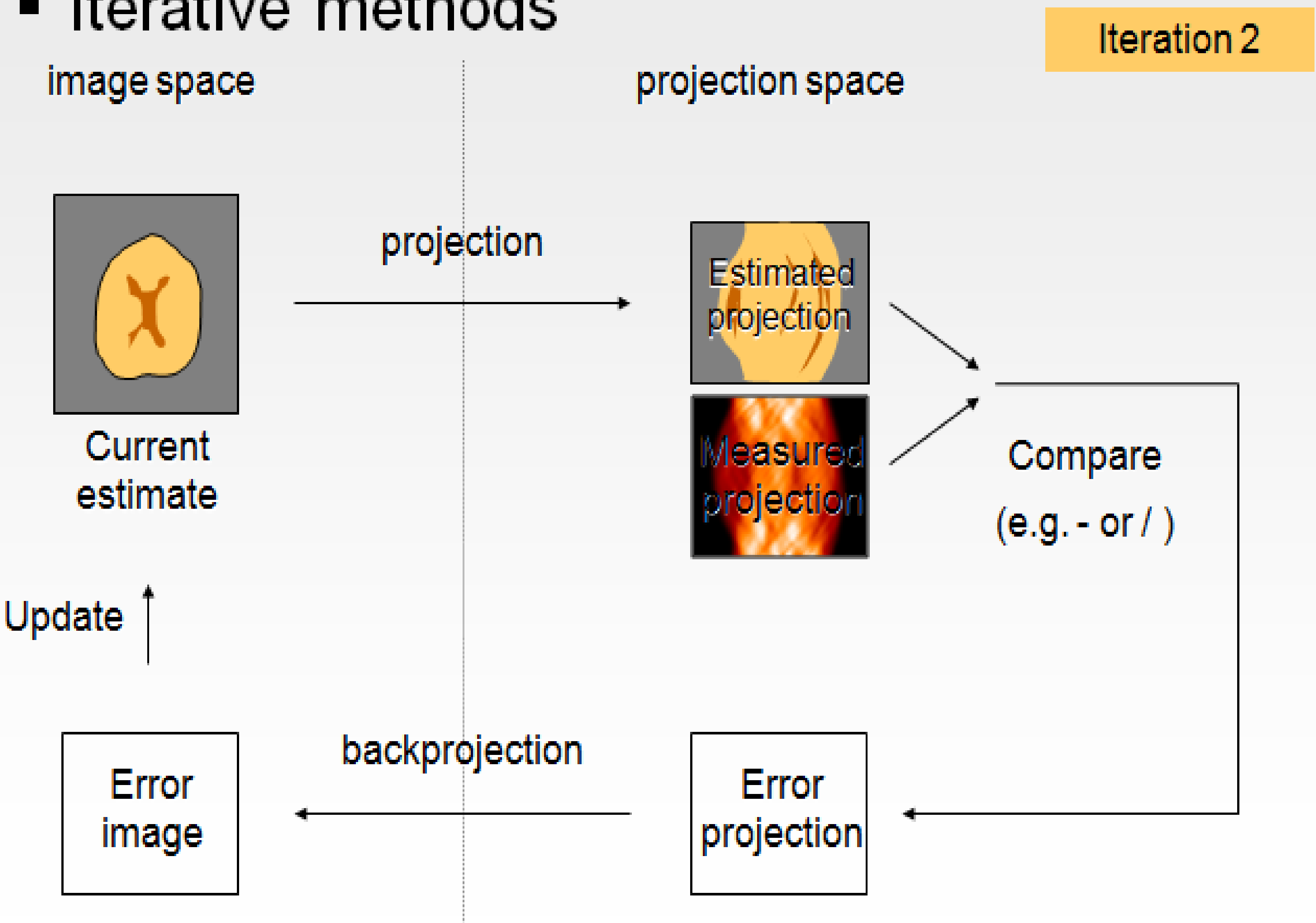

Object
Backprojection
4 projections
16 projections
128 projections
Filtered Backprojection

- # Iterative methods

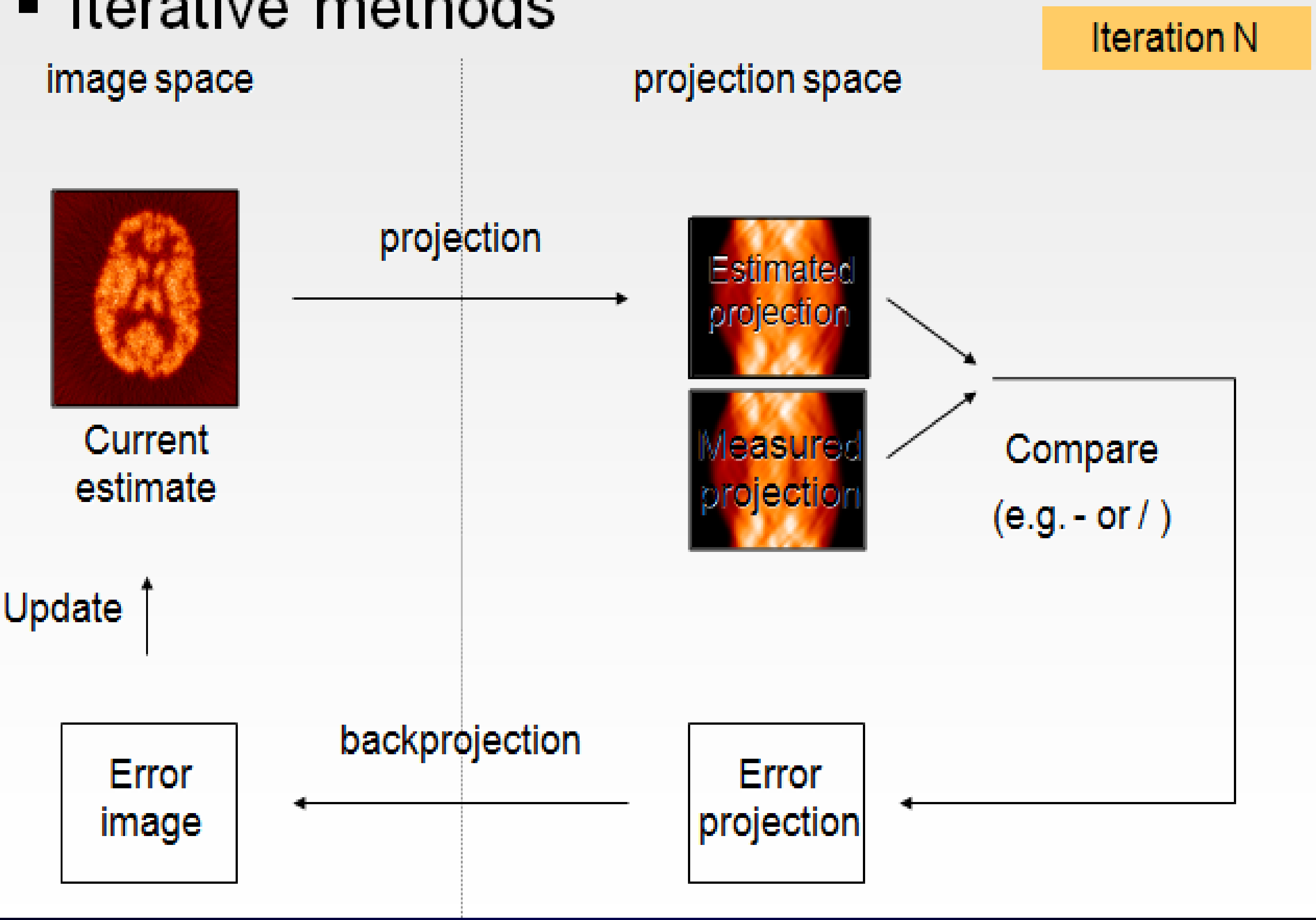
Iteration 1



- Iterative methods



- Iterative methods



Data Acquisition (Steps)

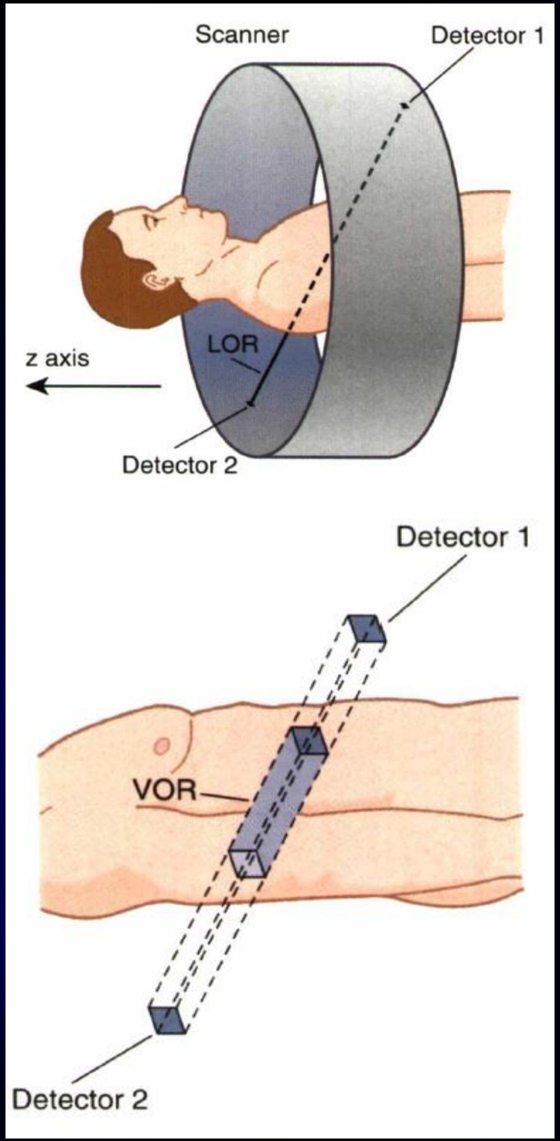
- In PET imaging, two 511 keV annihilation photons are detected in coincidence by two opposite detectors along a straight line, called the line of response (LOR), So:

- Three steps in PET data acquisition:

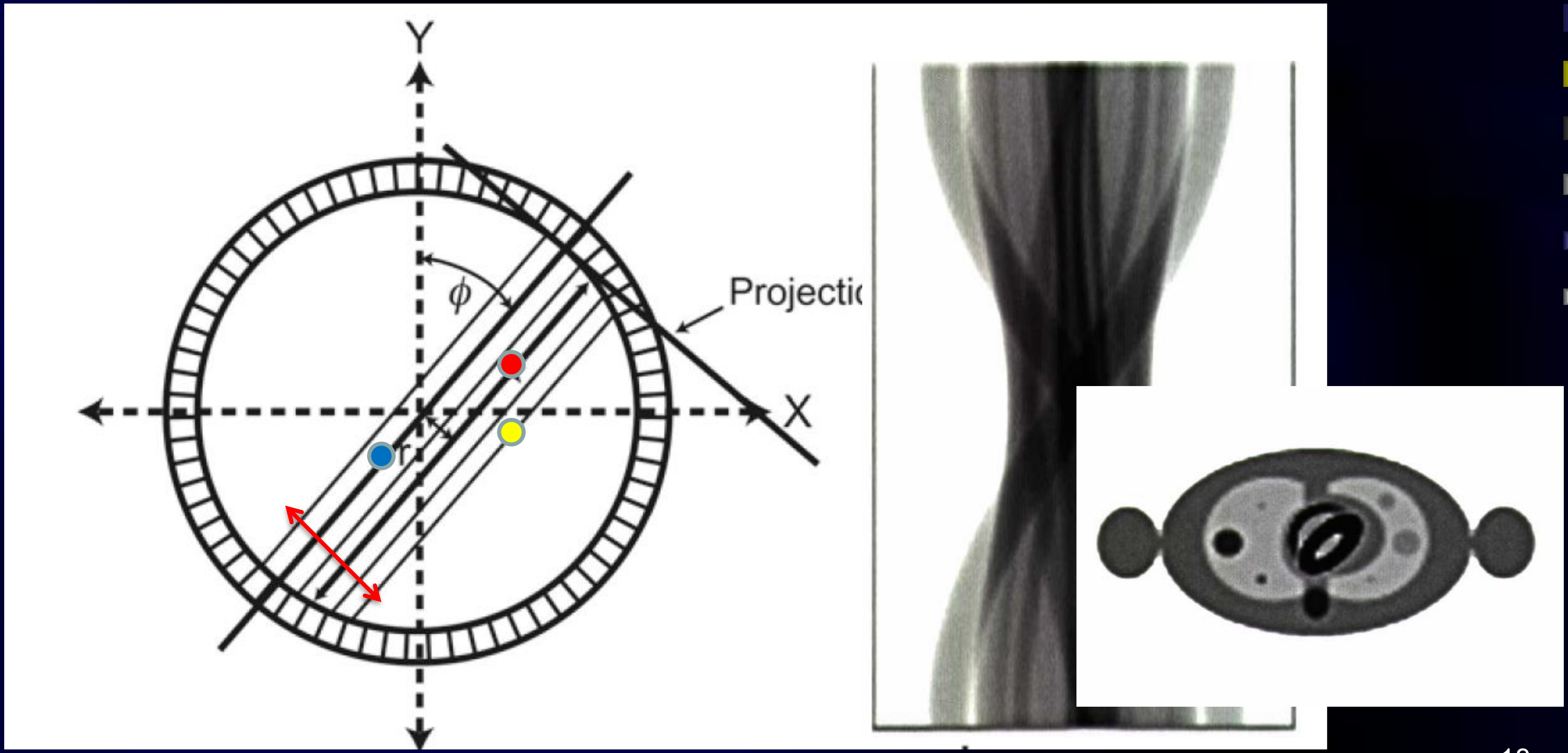
    1- Finding location of detector pair (PMT)

    2- Analyze pulses using PHA (PMT) & CW Circuit

    3- Sorting LOR positions in a "sinogram", via 1 to 1 arrangement



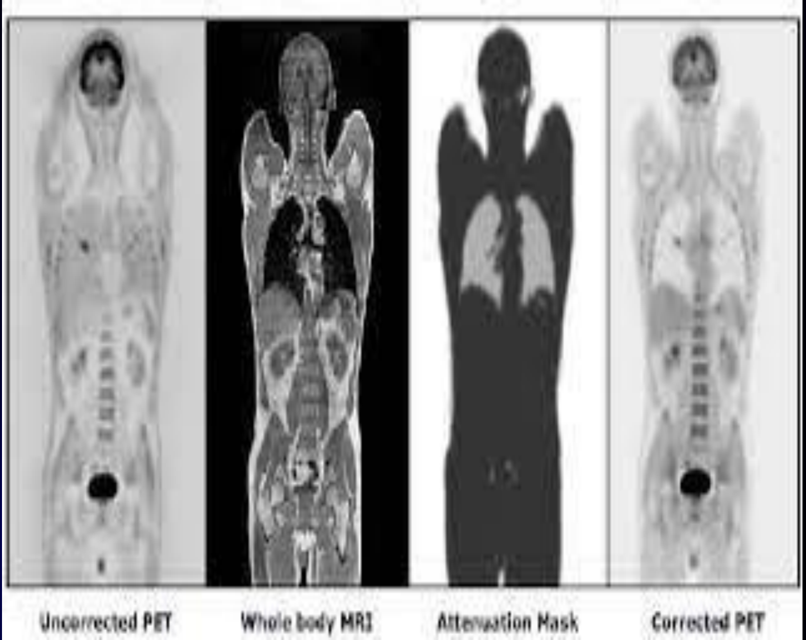
How do the lines of response organize into sinograms?



Data Corrections

Factors Affecting PET

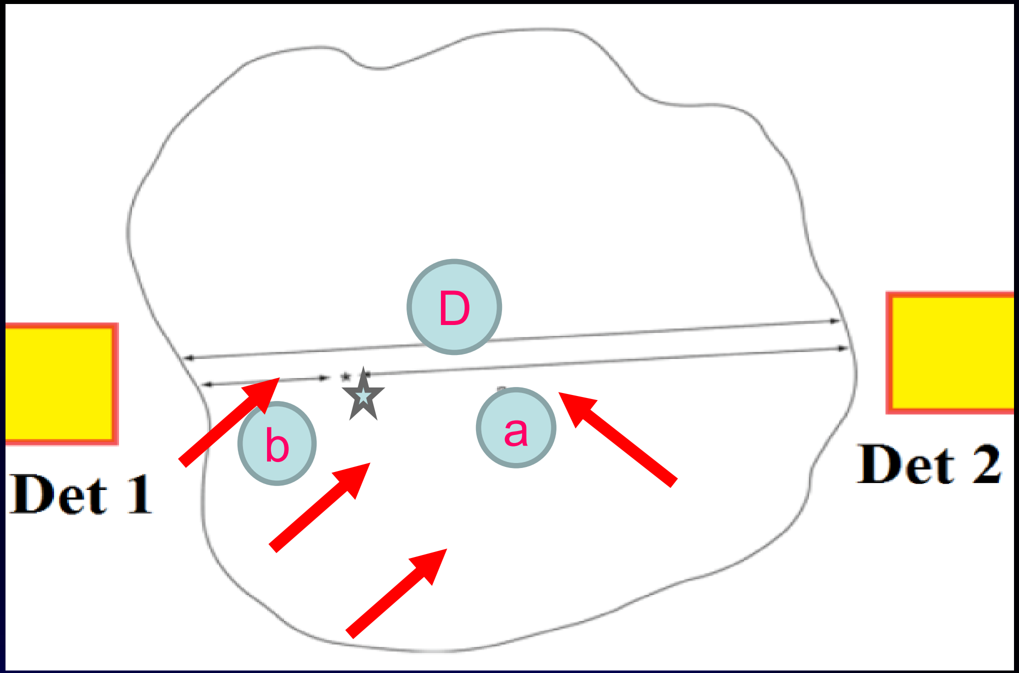
- Attenuation
- Random Coincidences
- Scatter Coincidences
- Parallax error
- Time of flight (TOF)



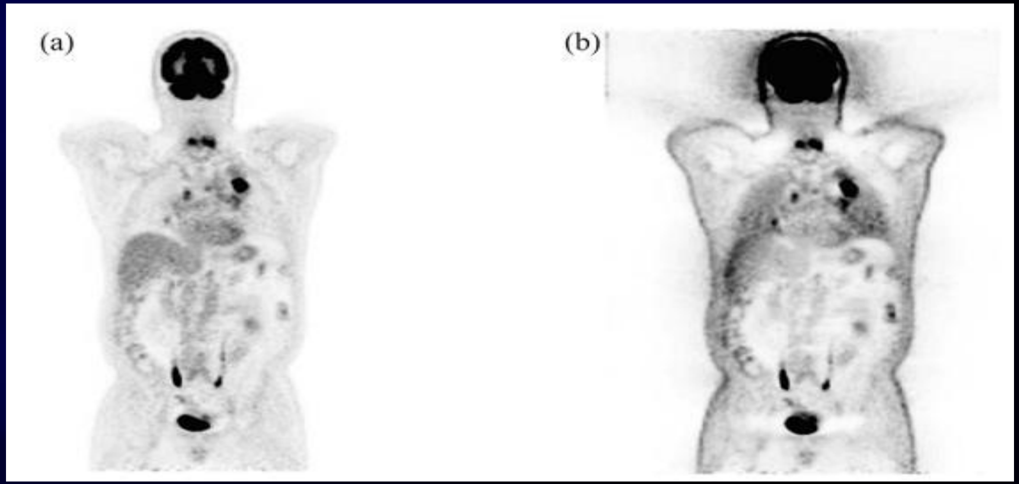
1) Attenuation Correction

Attenuation correction P for each pixel (i.e., each LOR) is given by:

$$P = e^{-\mu a} \times e^{-\mu b} = e^{-\mu(a+b)} = e^{-\mu D}$$



Linear attenuation coefficients and related thickness are derived from CT imaging.

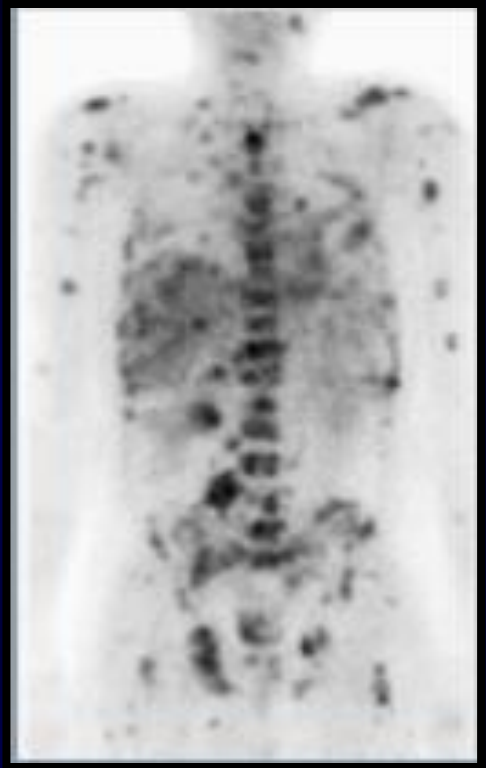


2) Random Coincidences

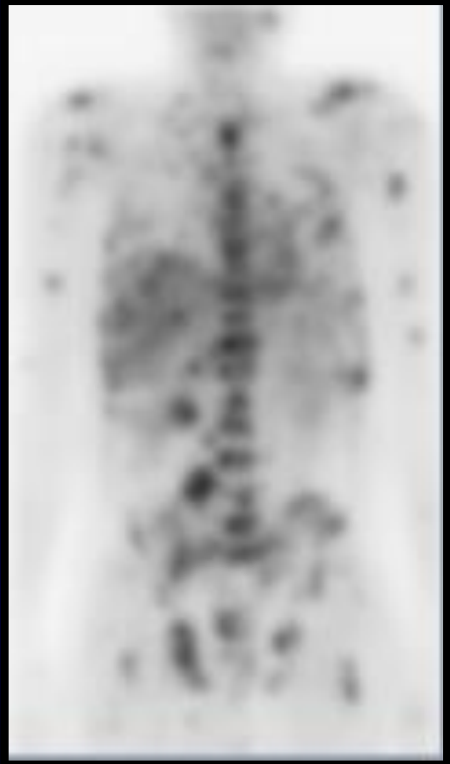
They create invalid spatial information & low contrast.
Randoms can equal or exceed true events number!

Consequences:

Reduced contrast
Reduced accuracy



True event



Random event

Correction method #1:

By separately measuring two single count rates, R_1 and R_2, of a radioactive source by each of the detector pair, Random count rate is:

$$R_c = 2\tau R_1 R_2$$

R_c will be subtracted from the prompt (T+R+S) count rate

Correction method #2:

Two coincidence circuits are employed

One is set at a standard coincidence timing window (e.g.12 ns)
the other at a delayed (e.g. 55 ns) time window (55–67 ns)

The counts in the standard time window: True + Scatter + Random
The counts in the delayed time window: Only random events

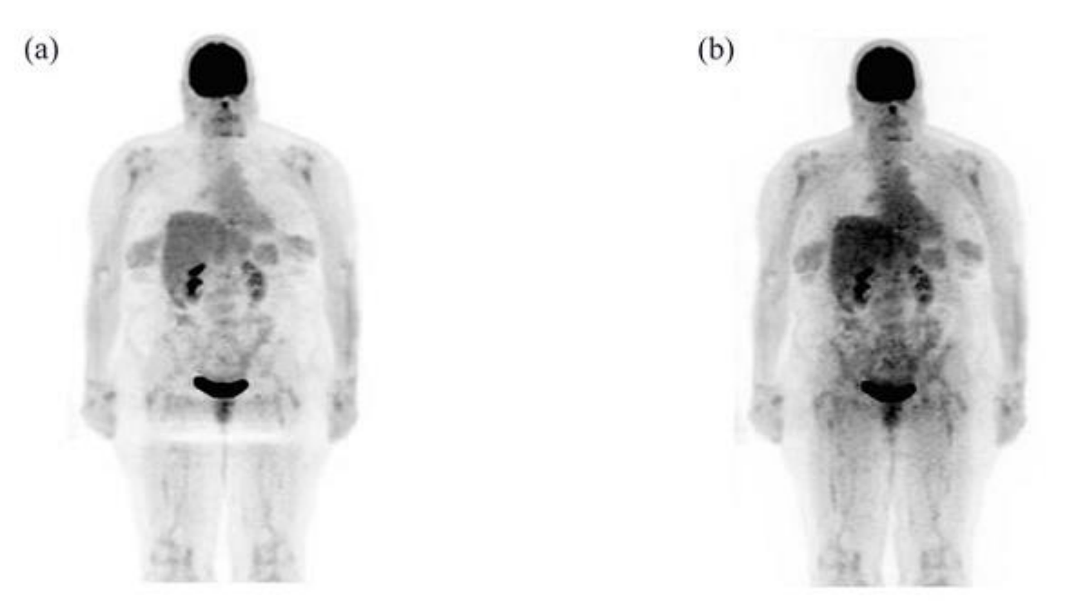
Assumption: Random counts will be the same in both coincidence and delayed coincidence windows.

3) Scatter Coincidences

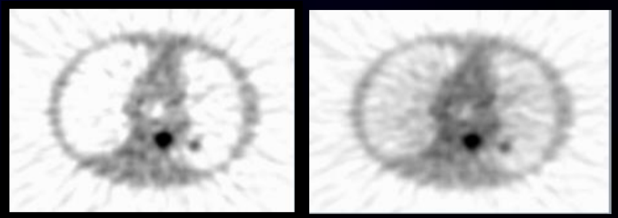
Background of the image is increased by these radiations with concomitant loss of image contrast and quantification accuracy.

But,... What affects Scattering?

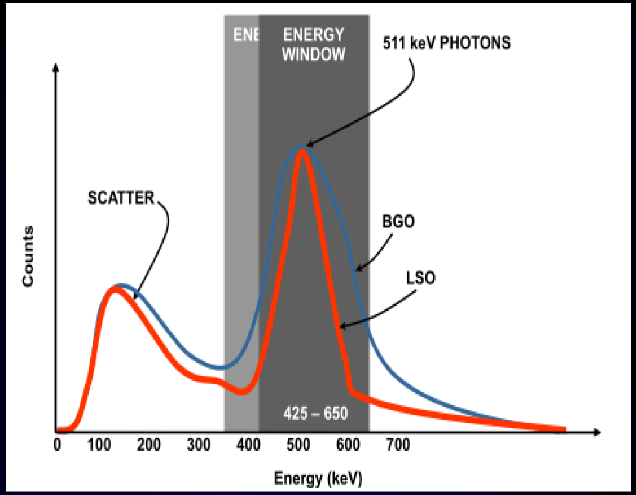
Density and depth of tissue, Density of detector, Activity, PHA window



Correction method #1:



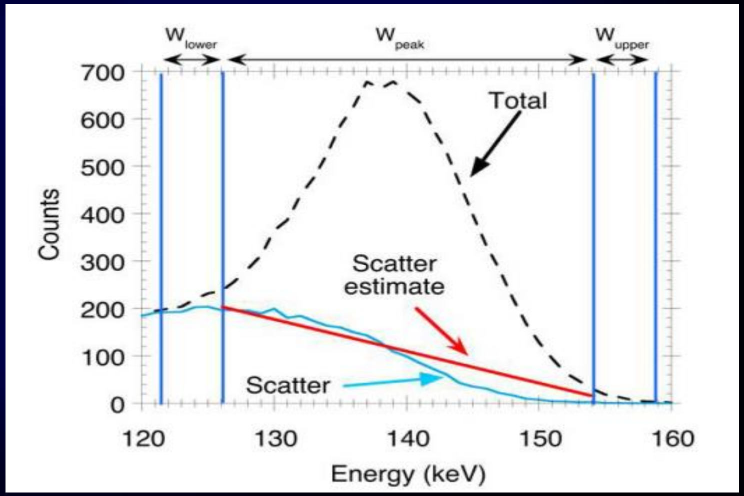
The weighted scatter counts are then subtracted from the measured photopeak counts to obtain the corrected counts for use in reconstruction.



This technique increases data processing time and the noise in the image.

Correction method #2:

Triple window technique has been employed using two overlapping low energy windows with a common upper energy level just below the photopeak window.

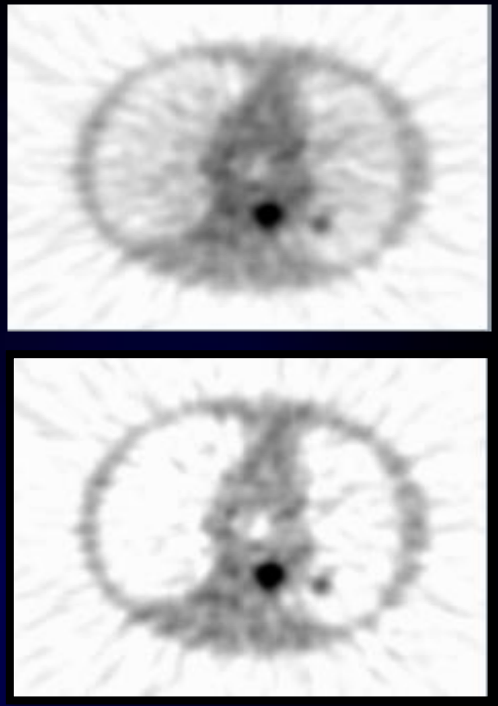


This technique has reasonable success.

Correction method #3:

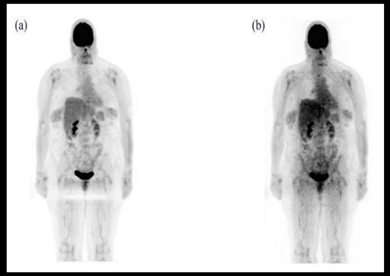
Theoretical models in which (after random corrections), Guassian or parabolic fit is applied to the scatter distribution outside the photopeak, then extrapolated to estimate the scatter contribution under the photopeak.

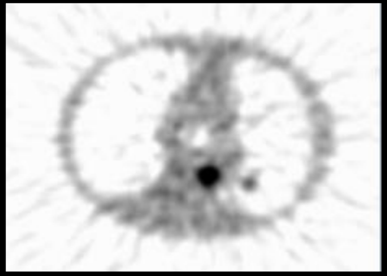
- ❑ **It works well in 2D PET Brain studies**
- ❑ **It is inaccurate in areas of high attenuation (e.g. thorax with arms down)**



Correction method #4:

Convolution method in which a scatter function is measured from a point source. Then it convolves with source distribution to estimate the scatter data

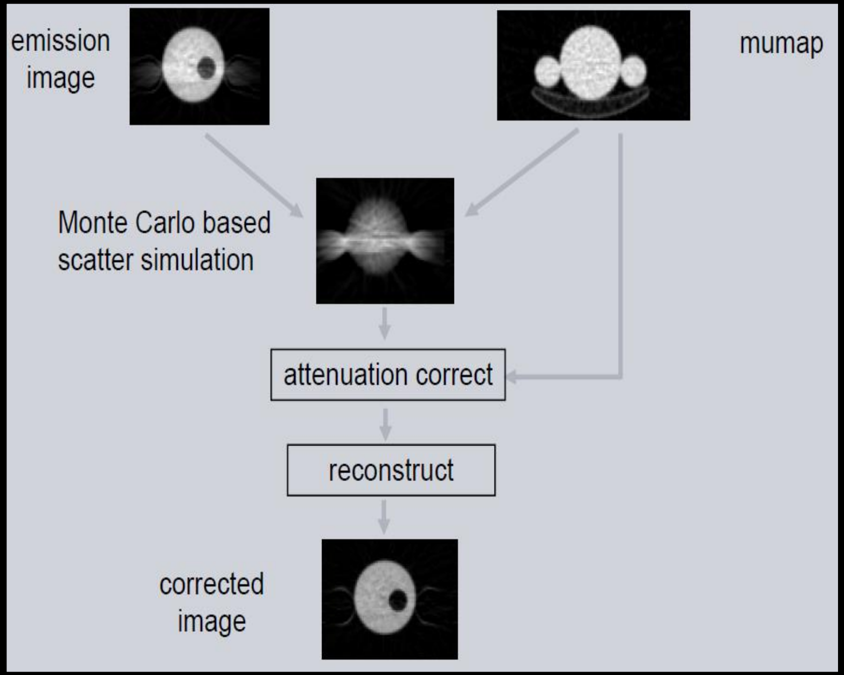




- ❑ It takes the scatter dependence on the position
- ❑ It is Computationally efficient

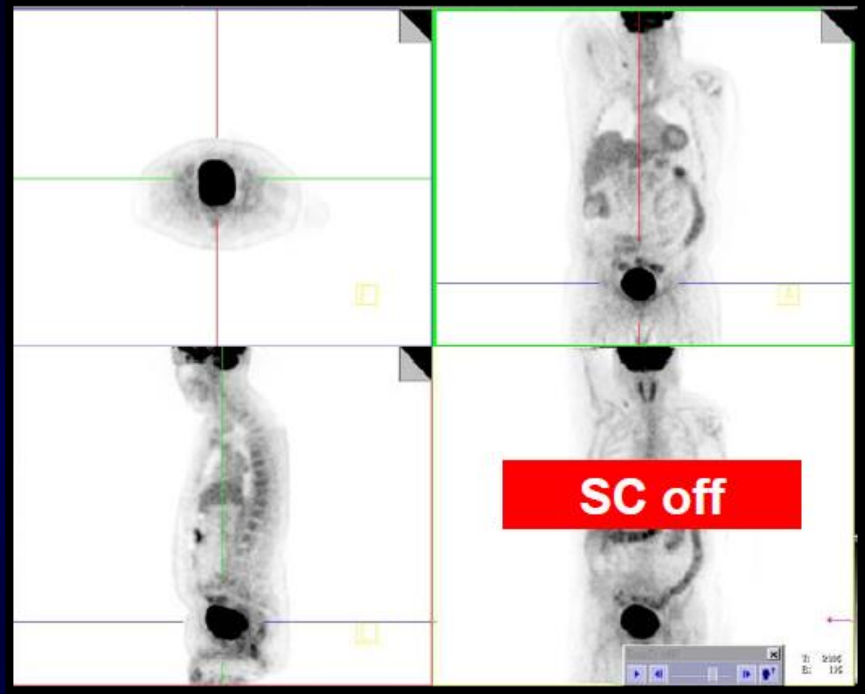
Correction method #5:

Monte Carlo method in which each interaction of photon in the patient and its detection in the block detector is traced in a simulation process.

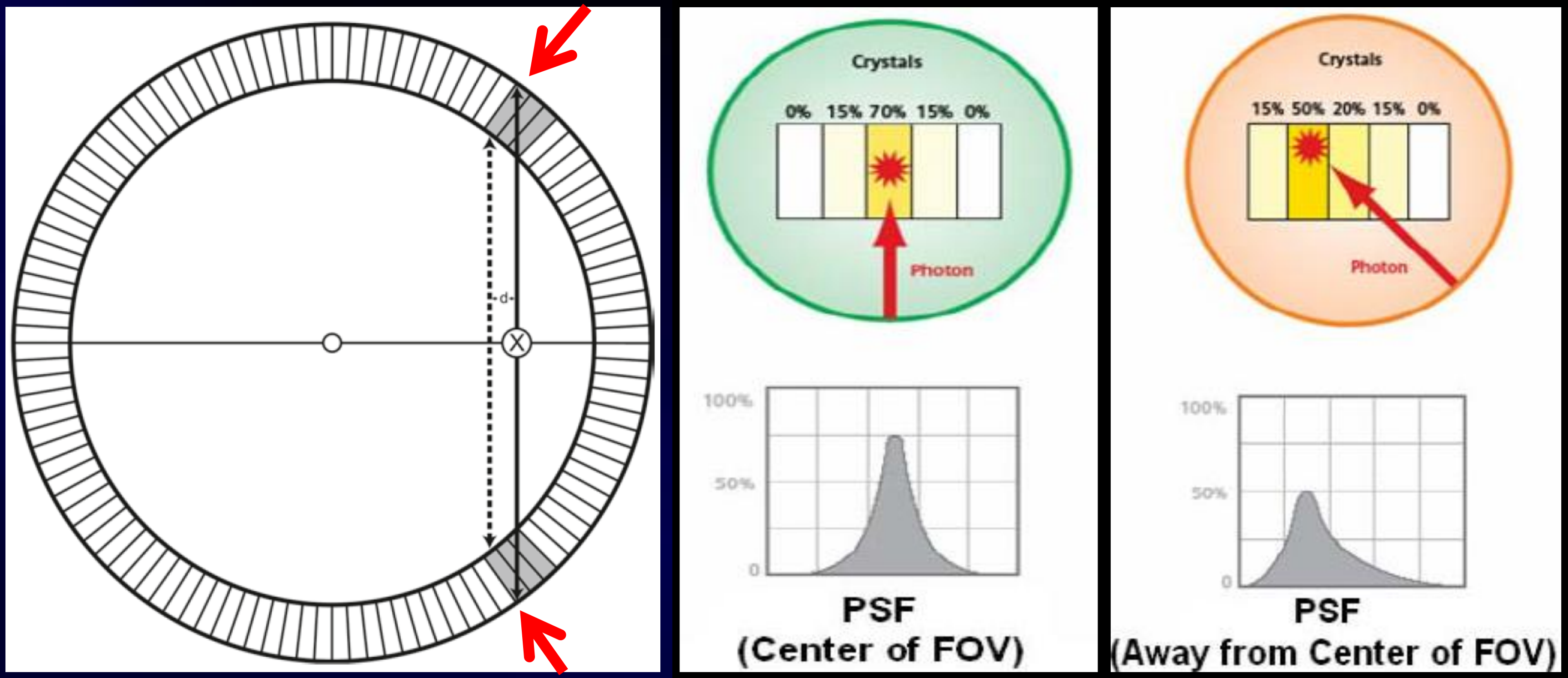


This method does not take into account scatter from outside the source.

We may see artifacts in scatter correction especially low adjacent activity areas around high activity concentrations overcorrects and make a photopenic area.



4) Parallax error (Radial Elongation- Radial Astigmatism)

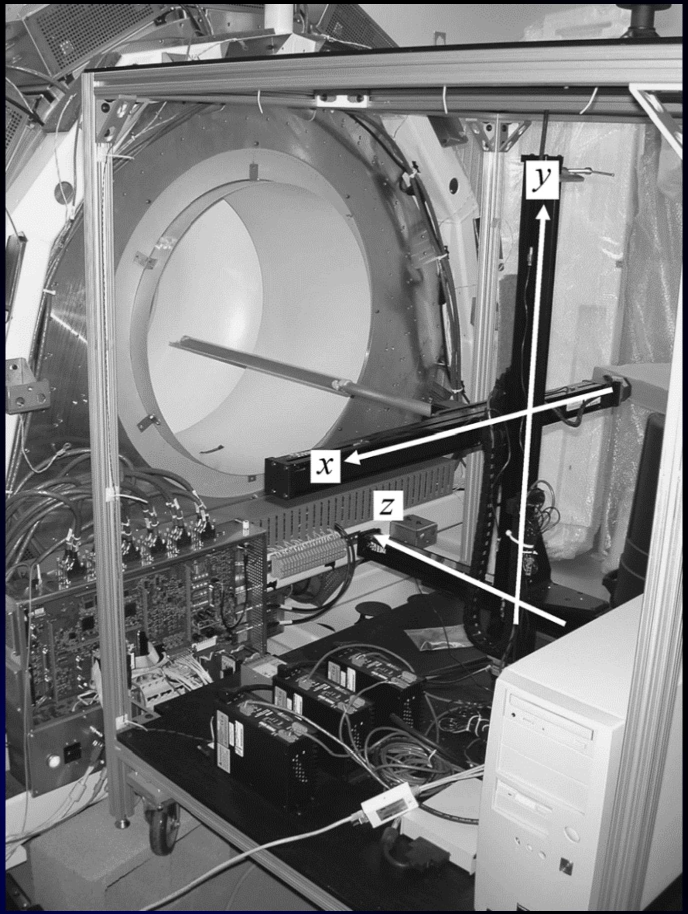


X, Y positioning of the detectors is defined by the dashed line some distance *d* away from the actual LOR. This effect results in some blurring of the image due to unknown depth of interactions, and worsens with the LORs farther away from the center and with a thicker detector.

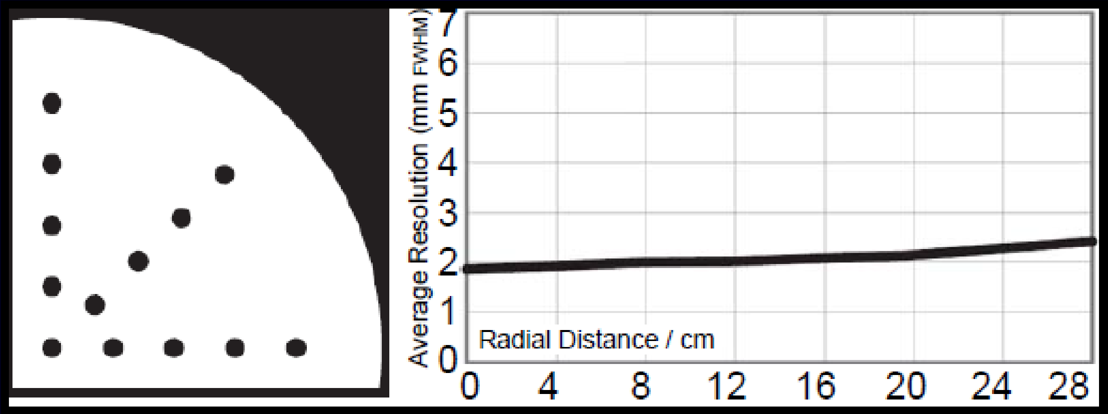
We know that Point Spread Function (PSF) describes response of imaging system to a point source.

A system that knows the response of a point source from everywhere in its field of view can use this information to recover the original shape and form of imaged objects.

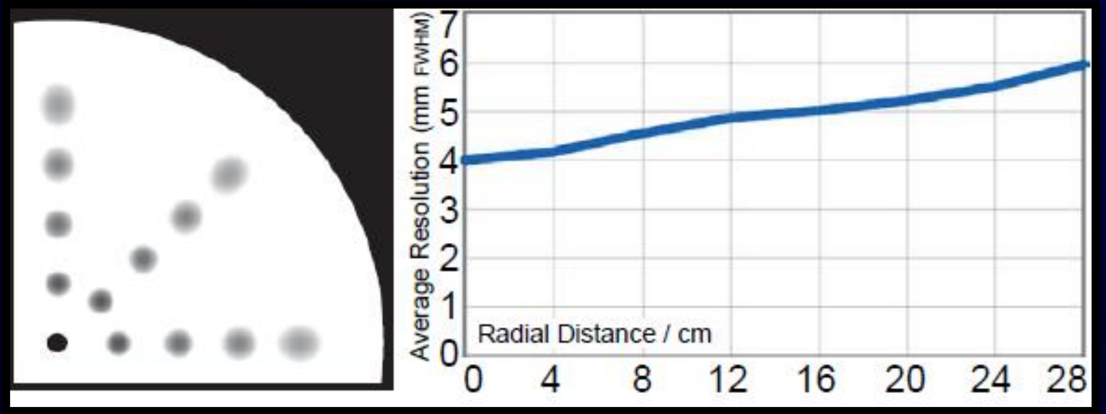
System corrects the LOR because of a better understanding of the PSF!



Robot to measure PSF



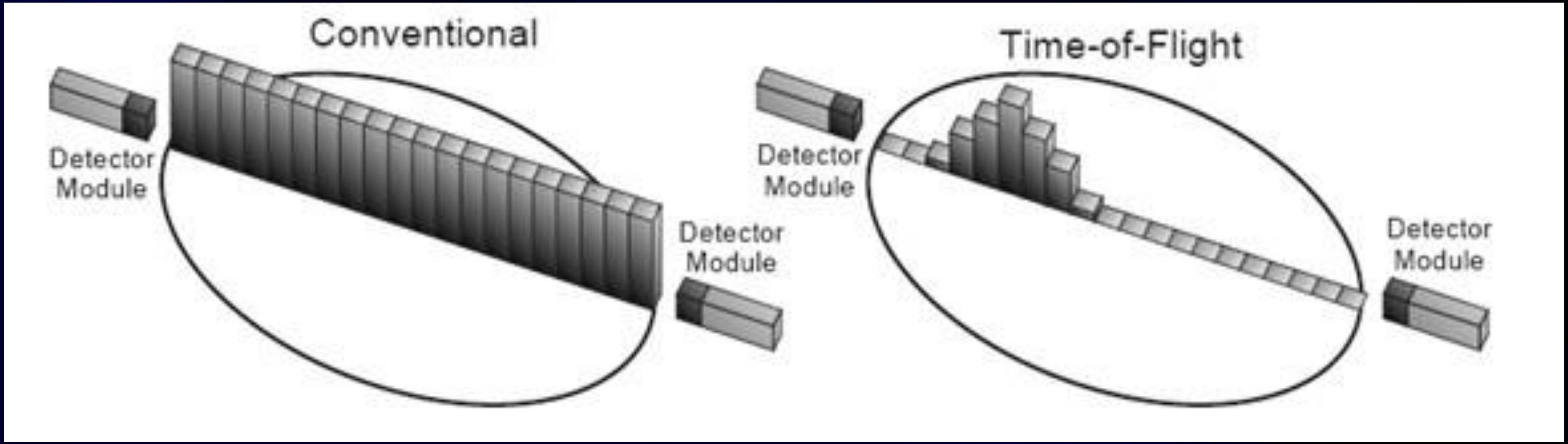
HD•PET improves image resolution



PET resolution is lost in the geometry of the detector

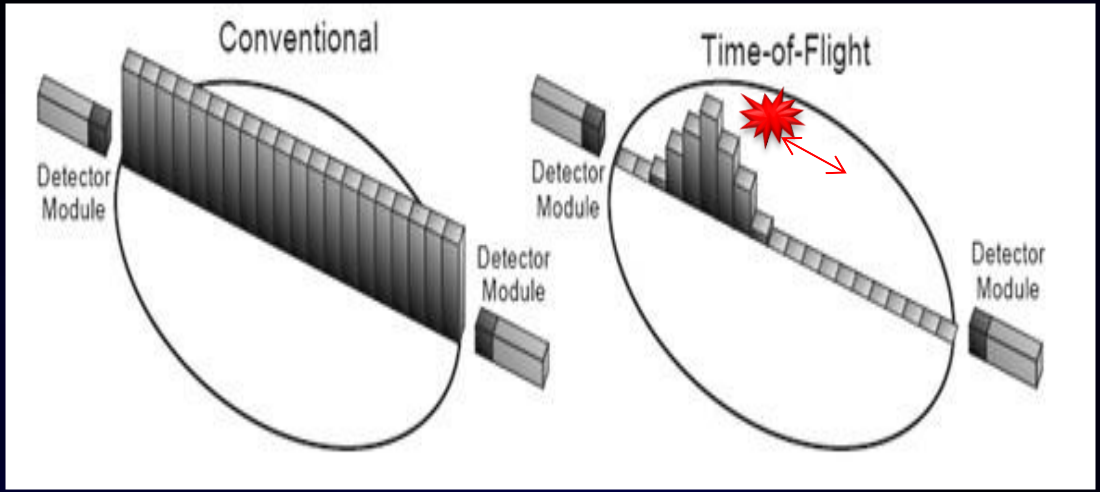
5) Time of Flight (TOF)

definition of the position of annihilation along the line of annihilation using the measured difference in arrival times



$\Delta t = Timing\ resolution = TOF\ Res.$

$$\Delta t = t_1 - t_2 = \frac{x + \Delta x}{C} - \frac{x - \Delta x}{C} = \frac{2.\Delta x}{C}$$

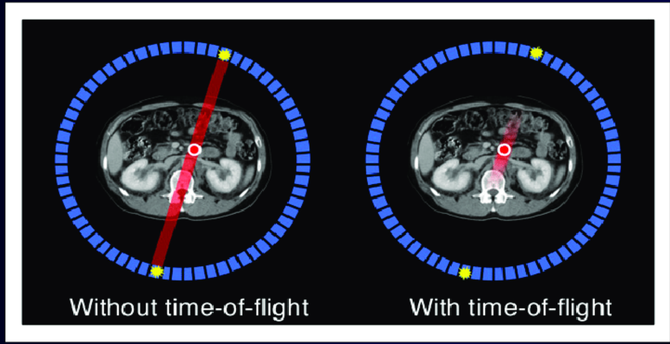


$$\Delta t = \frac{2.\Delta x}{C}$$

$$= TOF\ Res.$$

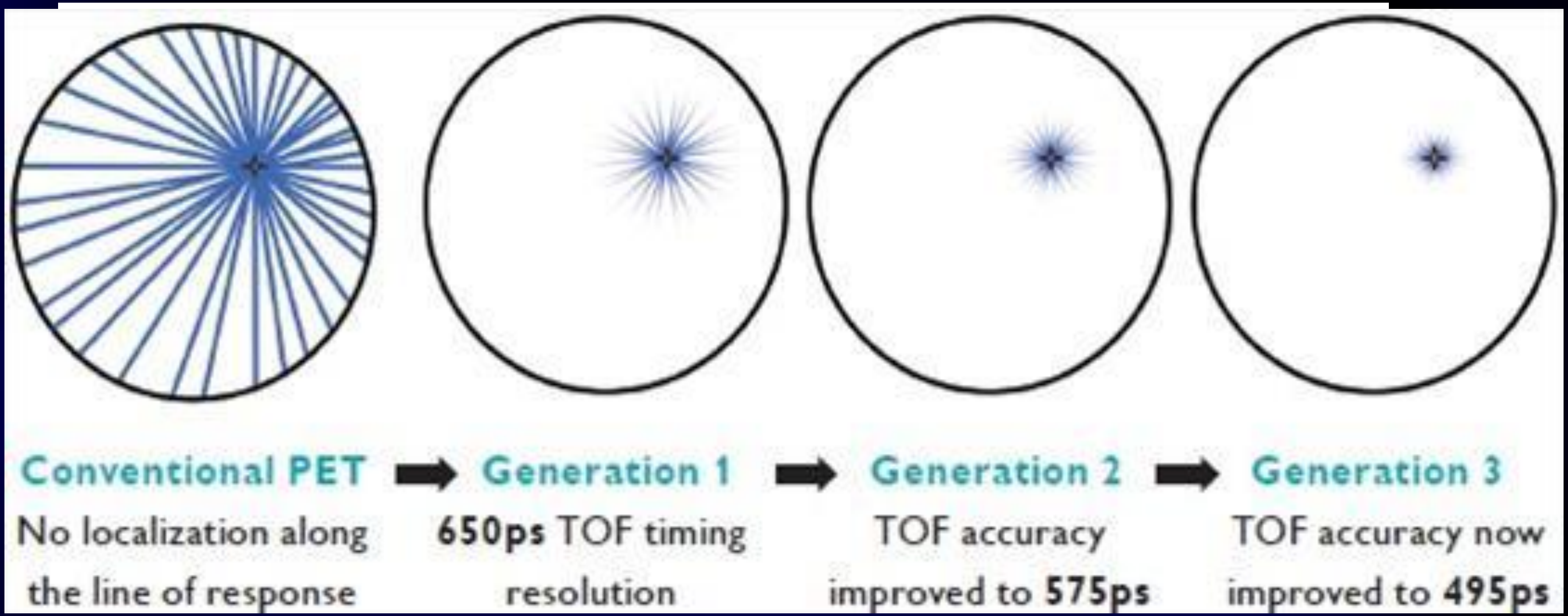
$$\Delta t = 300\ ps$$

$$\rightarrow \Delta x = \frac{C.\Delta t}{2} = \frac{3 * 10^\wedge 10\ {}^{cm}/_{s} * 300 * 10^\wedge{}^{-12}}{2} = \frac{9}{2} = 4.5\ cm$$



TOF current situation

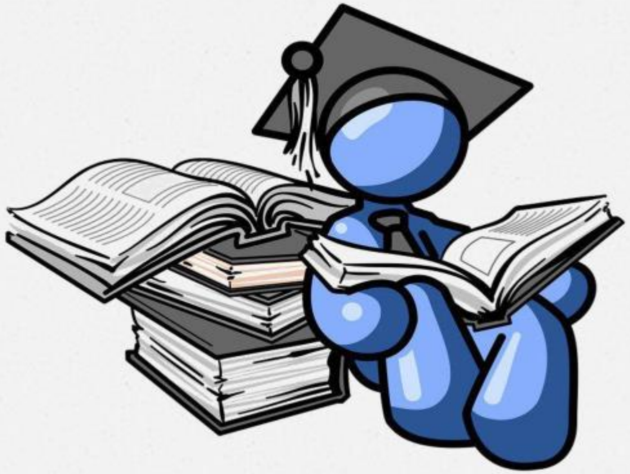
Best Current Timing Res. ~ 300 ps ~ 4.5 cm TOF Kernel



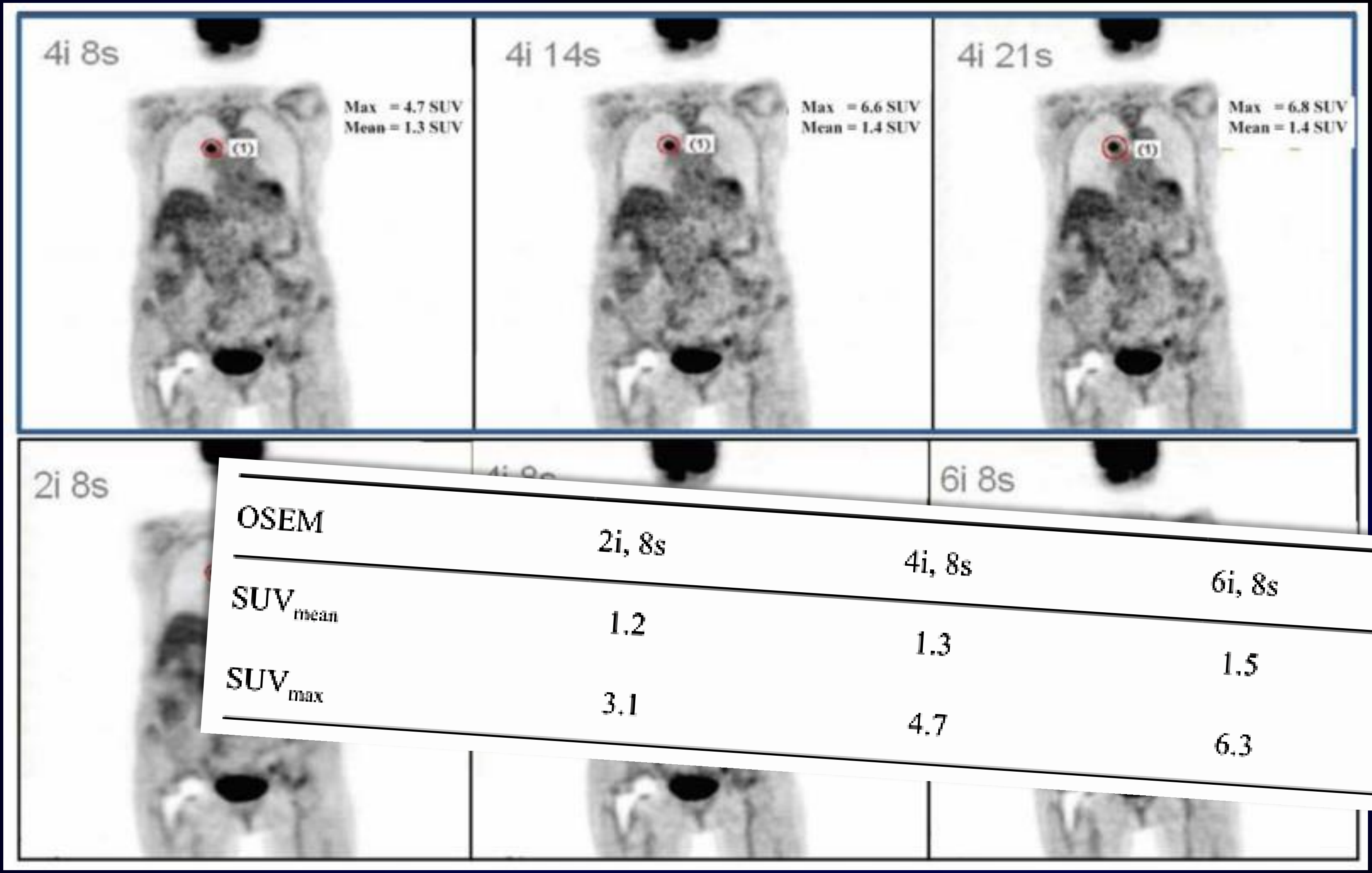
In a perfect TOF-PET system (TOF resolution→ ~0) image reconstruction would not become necessary!

Effects of Image Reconstruction Parameters on PET Images

- Visual assessment and image quality
- Quantification and harmonization

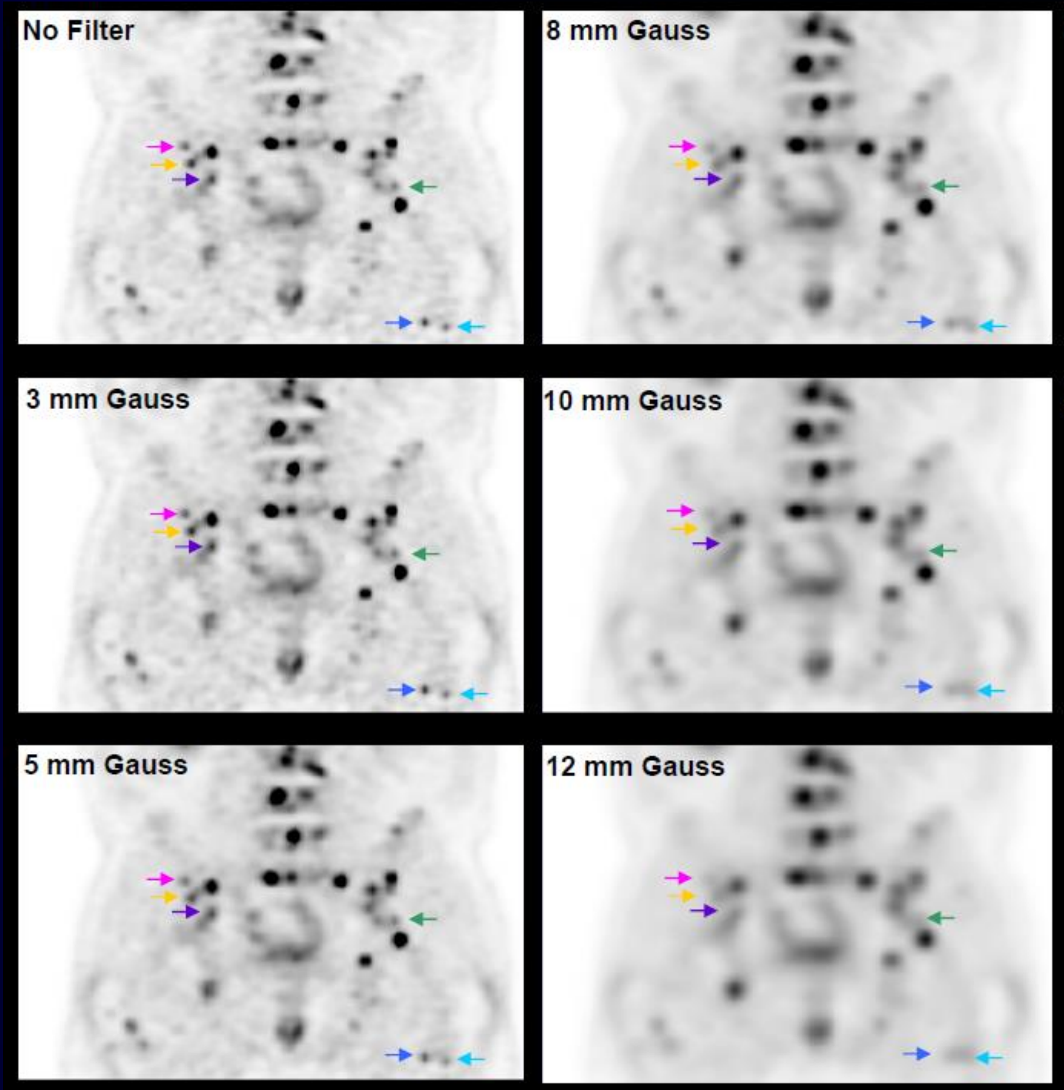


Iteration x subsets



OSEM	2i, 8s	4i, 8s	6i, 8s	4i, 14s	4i, 21s
SUV_{mean}	1.2	1.3	1.5	1.4	1.4
SUV_{max}	3.1	4.7	6.3	6.6	6.8

Post-smoothing filter



which one is the good one?

Post-smoothing filter

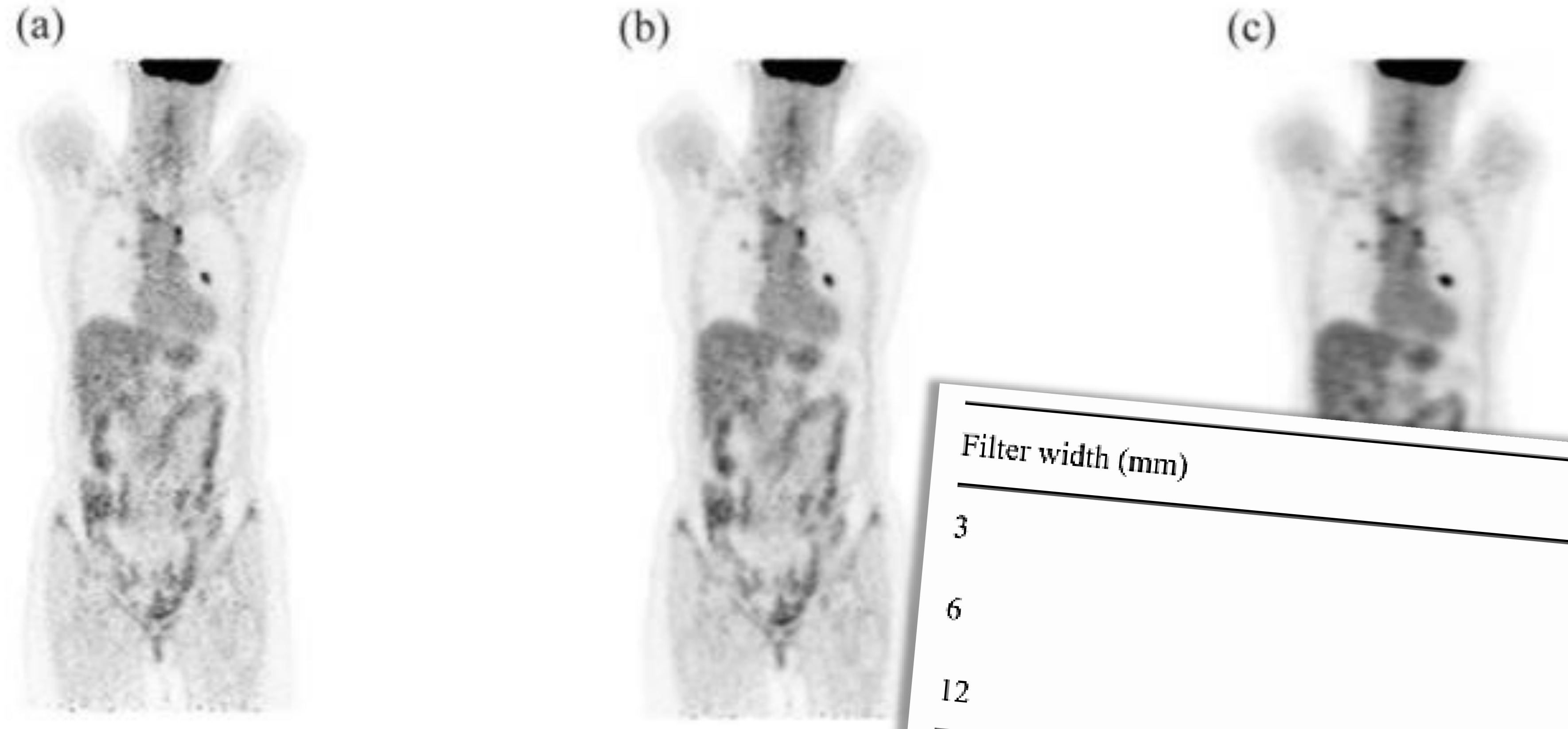
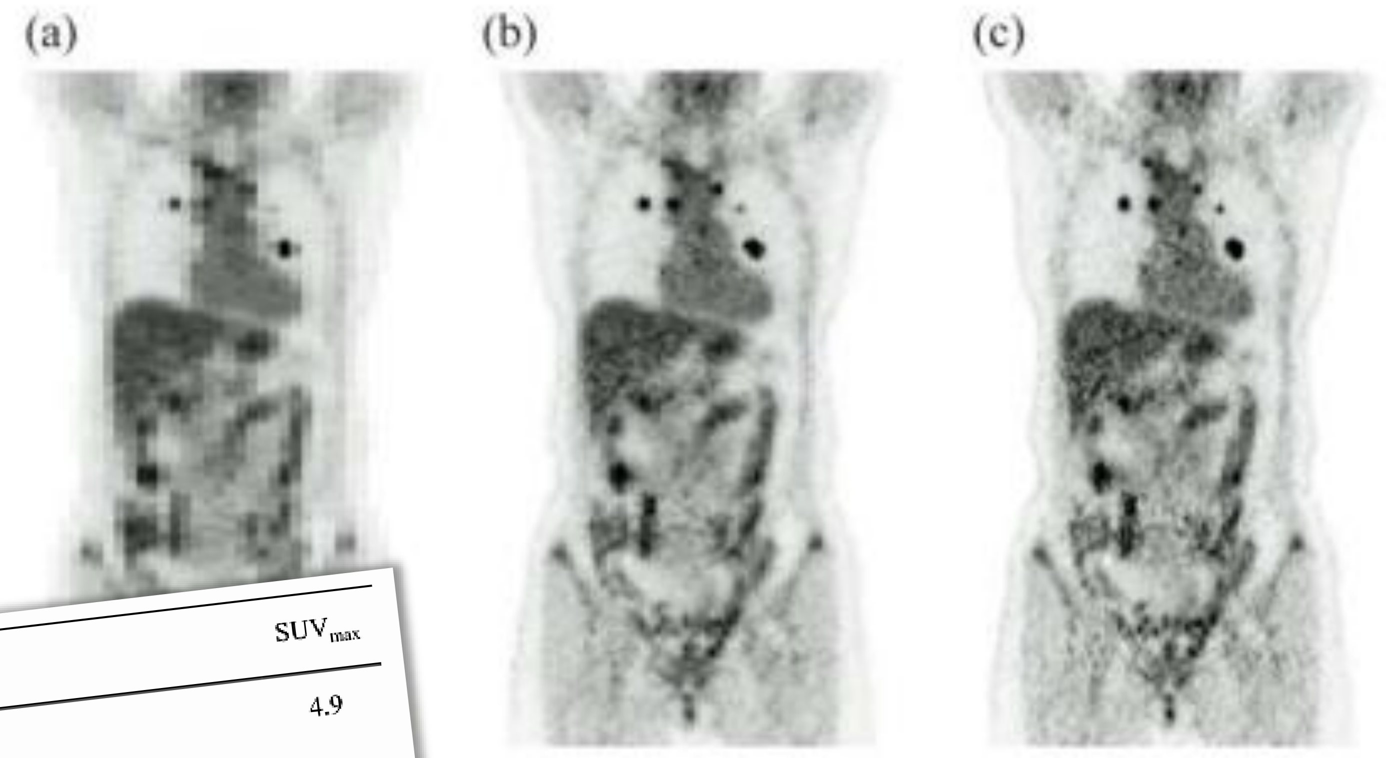


FIG. 2.15. Coronal FDG-PET image following post-reconstruction filters of 3 mm (a),

Filter width (mm)	SUV_{max}
3	6.4
6	5.5
12	3.3

Image matrix size



structed with a matrix size of 64 pixels (a), 128 pixels (b) and 256 pixels (c).

Matrix size	SUV_{max}
64	4.9
128	5.5
256	5.7

Point Spread Function (PSF)

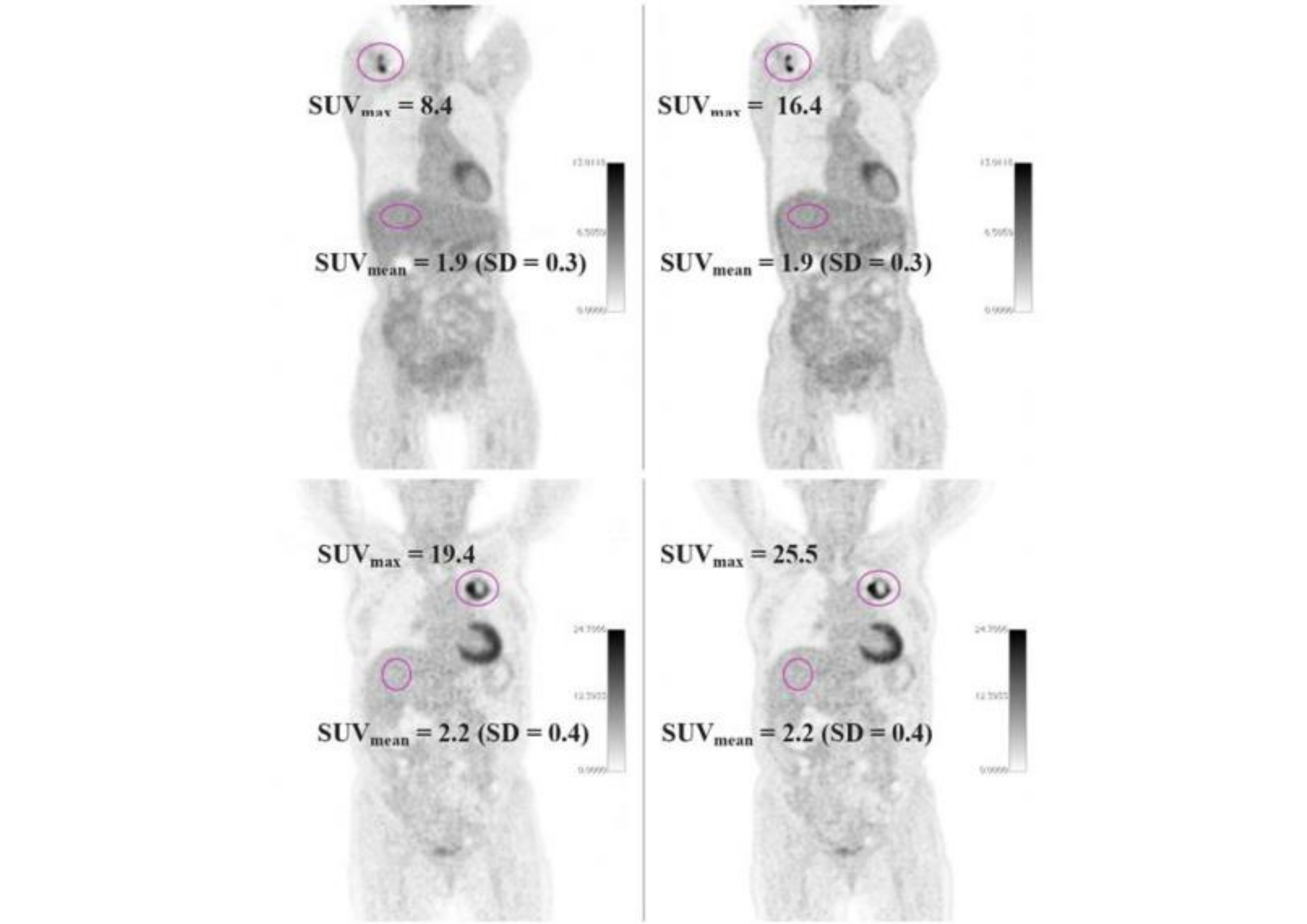


FIG. 2.18. Whole body PET image of two patients (top and bottom) reconstructed without (left) and with (right) point spread function. SD: standard deviation; SUV: standardized uptake value.

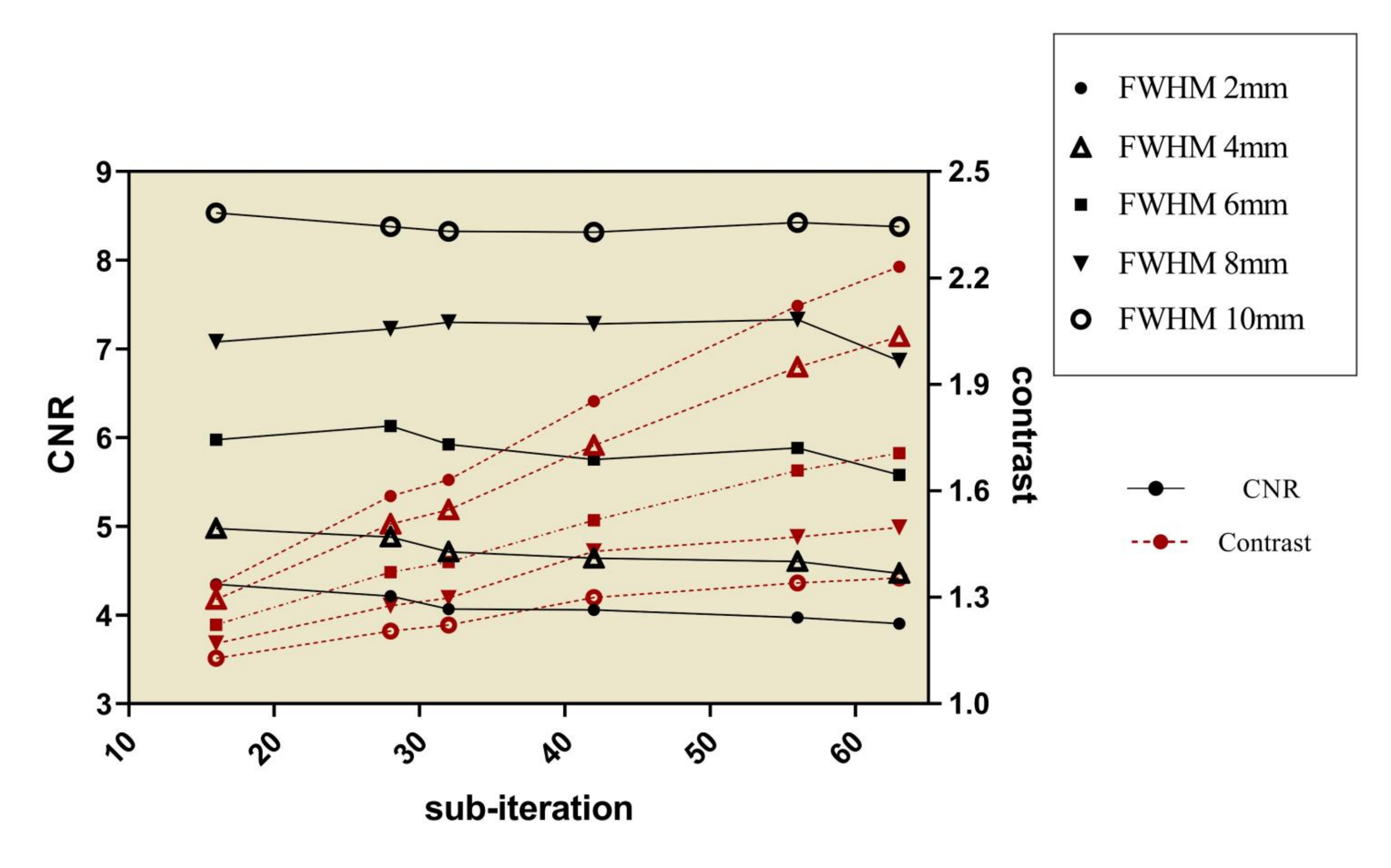
- PSF methods are available from vendors under different names (TrueX from Siemens, SharpIR from GE and Astonish from Philips)

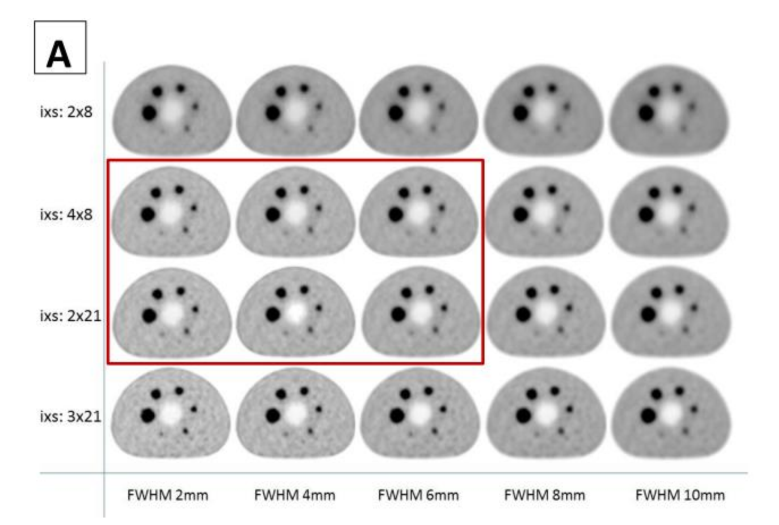
Optimization reconstruction parameters regarding image quality

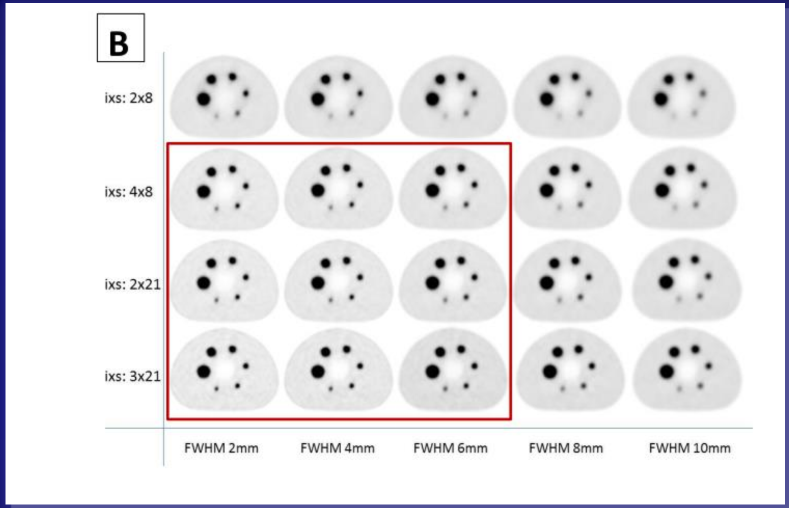
Vosoughi, 2024, IRJNM
Khazaee, 2017, nuclear medicine communication
Prieto , 2015, Physica Medica
Akamatsu , 2012, JNM

- assessment of iterations, subsets and FWHM of Gaussian filter on CNR, contrast and noise
- By increasing ixs and decreasing FWHM:

✓ CNR ↓
✓ Contrast ↑
✓ Noise ↑







The width of the Gaussian filter was more important than the number of sub-iterations in the detectability assessment.

Effects of reconstruction parameters on PET image quantification

Kelly , 2011, EJNMMI Research
Sunderland , 2015, JNM
Tsutsui , 2017, AOJNMB
Armstrong , 2017, Nuclear Medicine Communication
Bing Bai , 2011, IEEE

- Evaluation of various FWHM of Gaussian filter with different reconstruction sets on SUV in multicenter studies
- Using advanced reconstruction algorithms (PSF/TOF) overestimate the SUVmax ➡ edge artifact

⬇

Appropriate FWHM of Gaussian filter

Kelly and Declerck EJNMMI Research 2011, 1:16
http://www.ejnmmires.com/content/1/1/16

EJNMMI Research
a SpringerOpen Journal

ORIGINAL RESEARCH
Open Access

SUVref: reducing reconstruction-dependent variation in PET SUV

Matthew D Kelly* and Jerome M Declerck

Quantitative PET/CT Scanner Performance Characterization Based Upon the Society of Nuclear Medicine and Molecular Imaging Clinical Trials Network Oncology Clinical Simulator Phantom

John J. Sunderland[1] and Paul E. Christian[2]

Asia Oceania Journal of Nuclear Medicine & Biology
http://aojnmb.mums.ac.ir
AOJNMB

Characteristics of Smoothing Filters to Achieve the Guideline Recommended Positron Emission Tomography Image without Harmonization

Yuji Tsutsui[1, 2*], Shinichi Awamoto[1], ...

Shingo Baba[3], ...

Nuclear Medicine Communications

Technical note

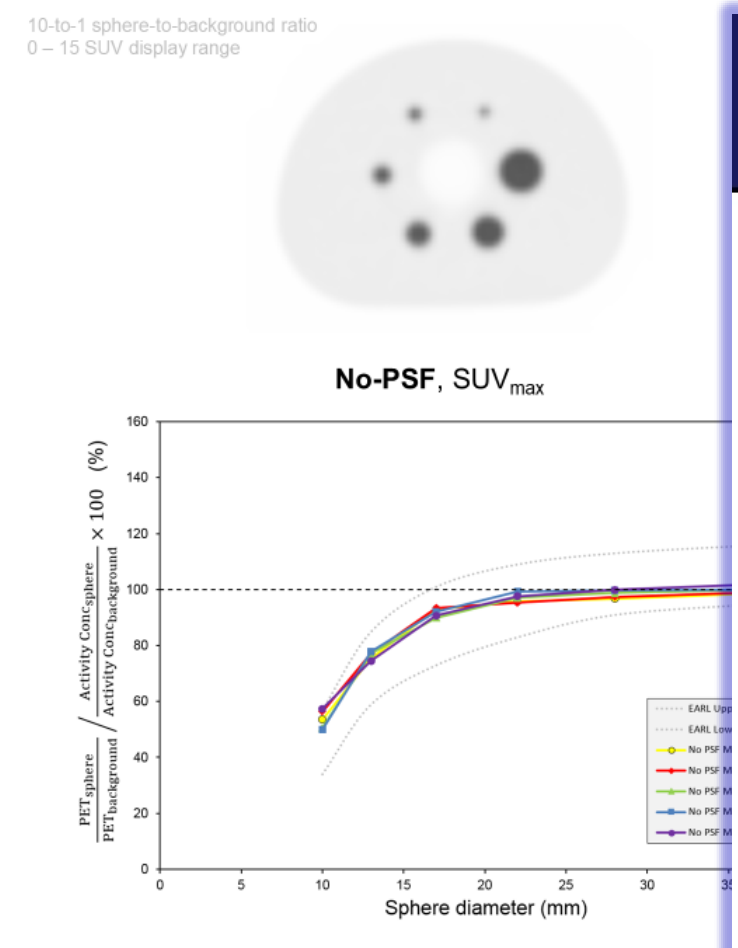
Harmonizing standardized uptake value recovery between two PET/CT systems from different manufacturers when using resolution modelling and time-of-flight

Ian S. Armstrong[a], Katharine E. Thomson[b], Lisa M. Rowley[c] and Daniel R. McGowan[d,e]

The Effect of Edge Artifacts on Quantification of Positron Emission Tomography

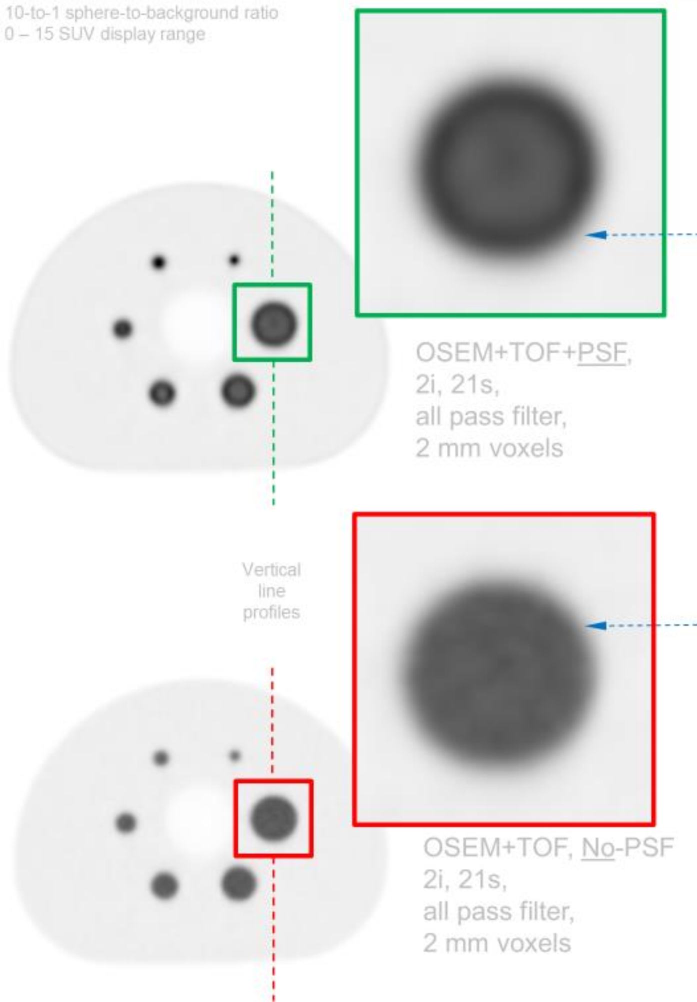
Bing Bai, Member, IEEE and Peter D. Esser, Member, IEEE

No-PSF vs. PSF



OSEM+TOF, 2i, 21s, 5 mm Gaussian, **4 mm vox**

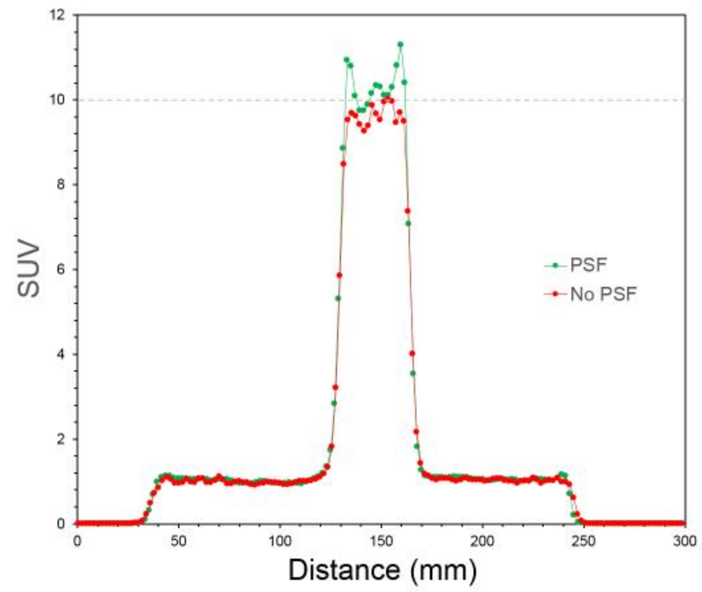
Edge Artifact



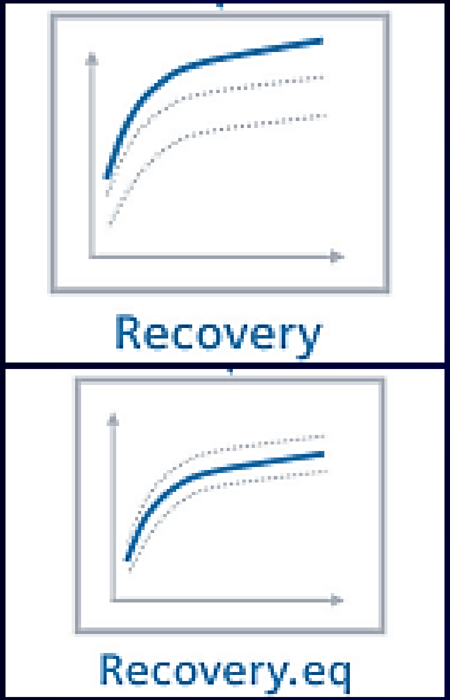
- Image reconstruction with PSF is associated with edge artifacts (Politte & Snyder 1988)

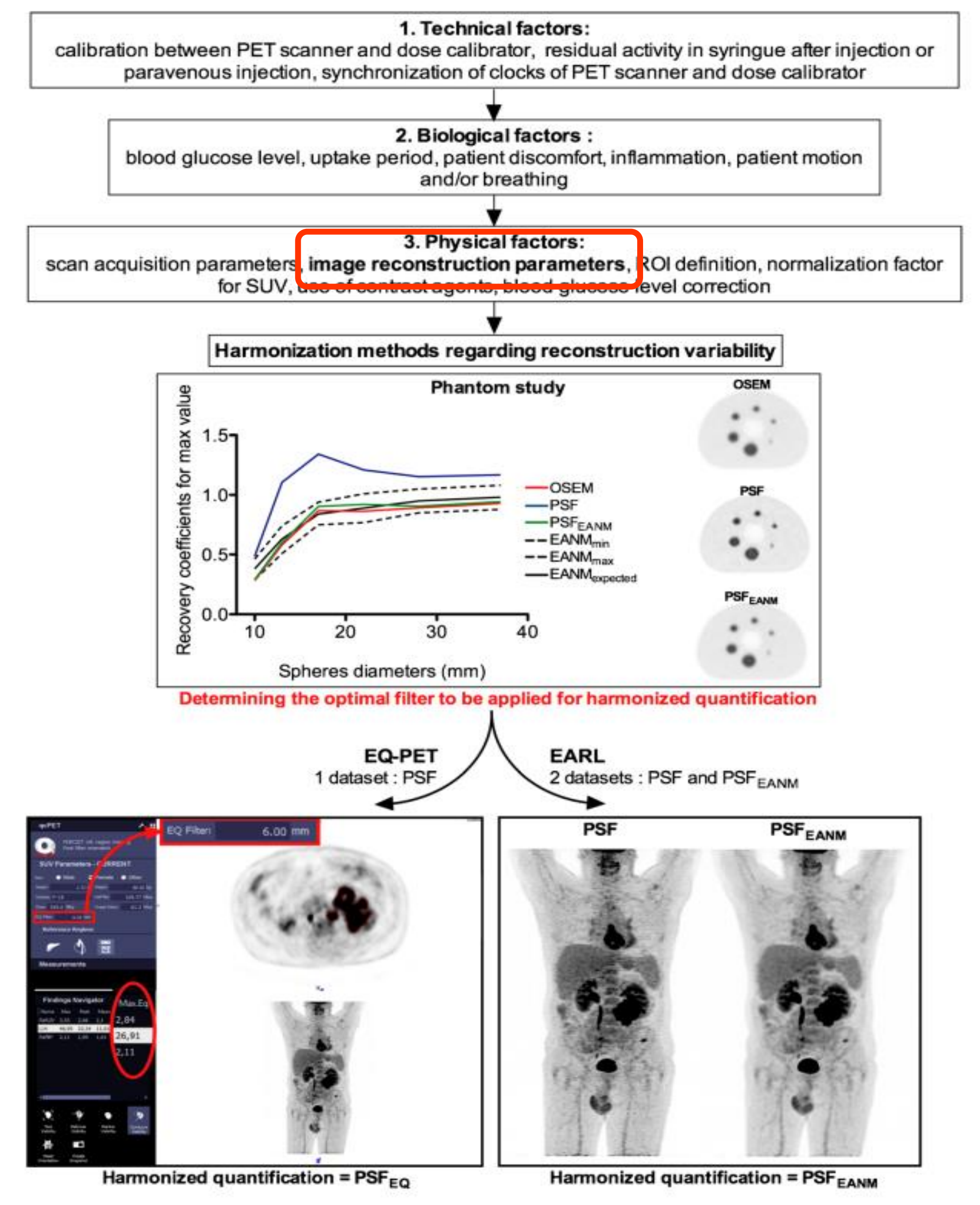
Edge artifact due to PSF.

No edge artifact with No-PSF.



Harmonization





Eur J Nucl Med Mol Imaging (2017) 44 (Suppl 1):S17–S31
DOI 10.1007/s00259-017-3740-2

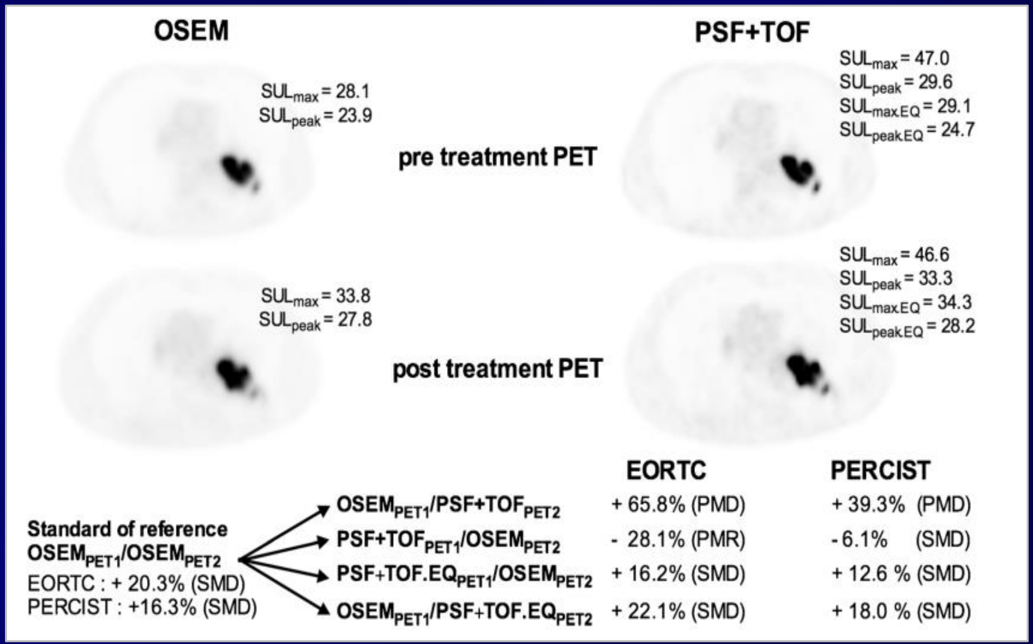
CrossMark

REVIEW ARTICLE

EANM/EARL harmonization strategies in PET quantification: from daily practice to multicentre oncological studies

Nicolas Aide[1,2] · Charline Lasnon[2,3] · Patrick Veit-Haibach[4,5] · Terez Sera[6] · Bernhard Sattler[7] · Ronald Boellaard[8,9]

Received: 19 April 2017 / Accepted: 24 April 2017 / Published online: 16 June 2017

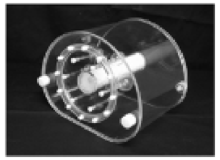
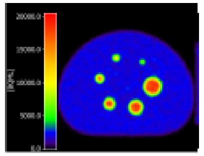
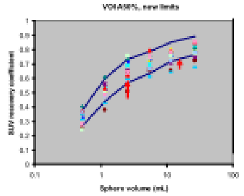


Multi-center QC and calibration

RESEARCH 4 LIFE

- Calibration QC specification:
  - maximum allowable calibration deviation = + or – 10% (global)

- SUV recovery specifications:
  - for SUVmax (focus –as SUVmax is used clinically!)
  - for SUVmean

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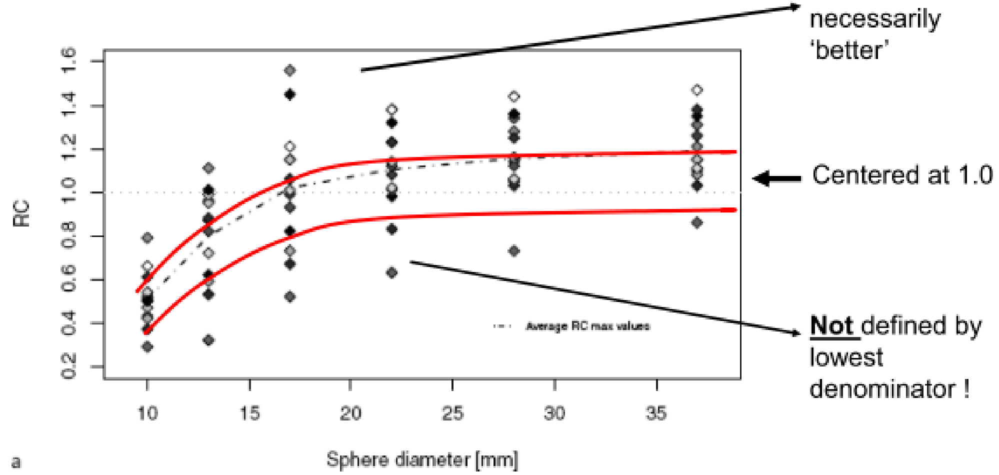
RESEARCH 4 LIFE

Realistic/EARL



Vosoughi, 2023, QIMS

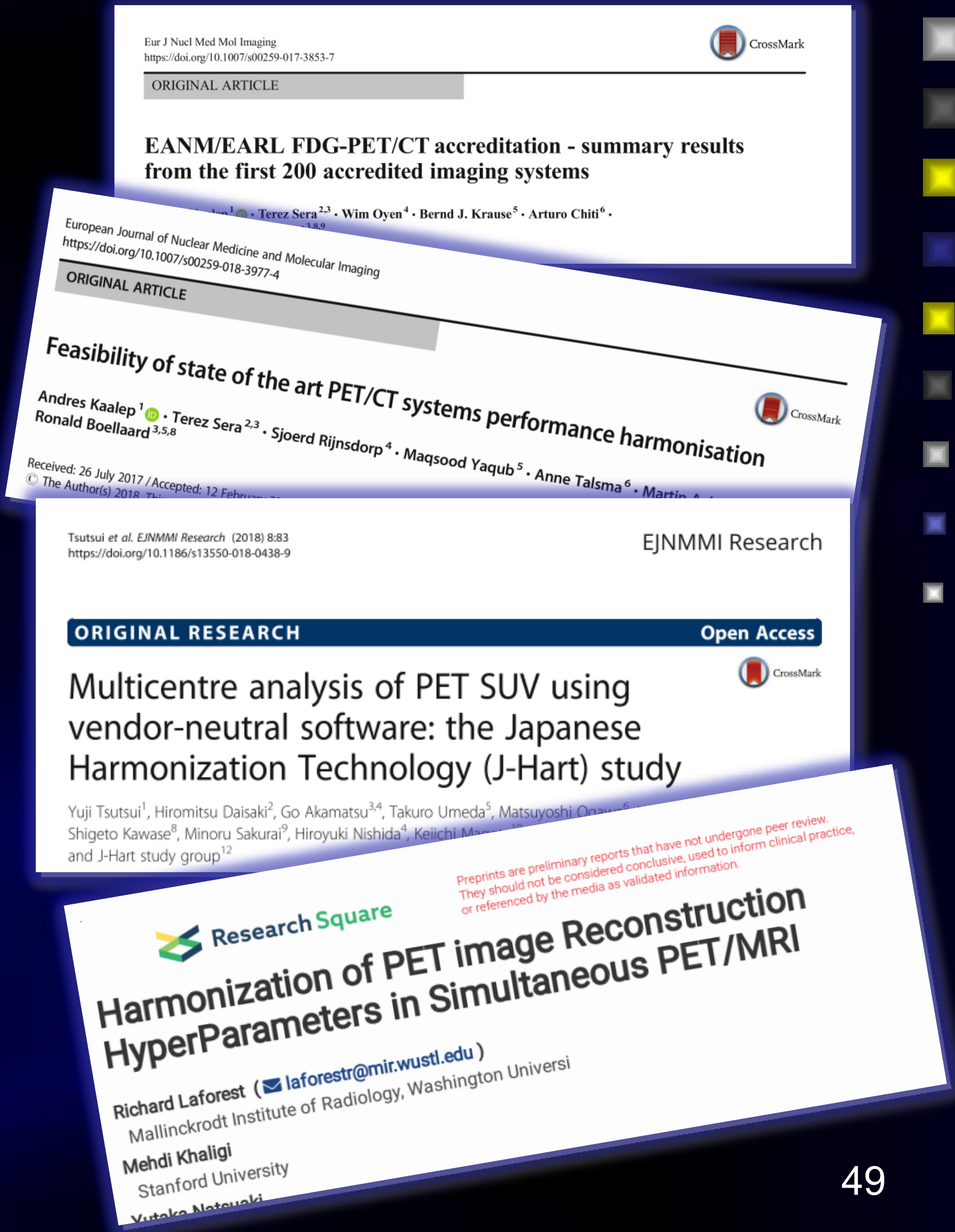
Kaalep, 2017, EJNMMI

Kaalep, 2018, EJNMMI

Tsutsui , 2018, EJNMMI Research

Laforest , 2020, Research Square

- **Techniques used for harmonization**
  - Variations due to the performance of PET/CT systems are reduced when RCs are within the acceptable EARL range.
  - Feasibility of harmonization and provision of new reference criteria to achieve higher RCs
  - Modification of reconstruction protocols by applying appropriate FWHM of Gaussian filter brings RCs values of different scanners closer together
  - Increasing Reproducibility and Repeatability



Quant Imaging Med Surg. 2023 Feb 8;13(4):2218–2233. doi: 10.21037/qims-22-443

Multicenter quantitative ^{18}F-fluorodeoxyglucose positron emission tomography performance harmonization: use of hottest voxels towards more robust quantification

Habibeh Vosoughi [1,^], Mehdi Momennezhad [2], Farshad Emami [3], Mohsen Hajizadeh [1], Arman Rahmim [4,5], Parham Geramifar [6,^,✉]

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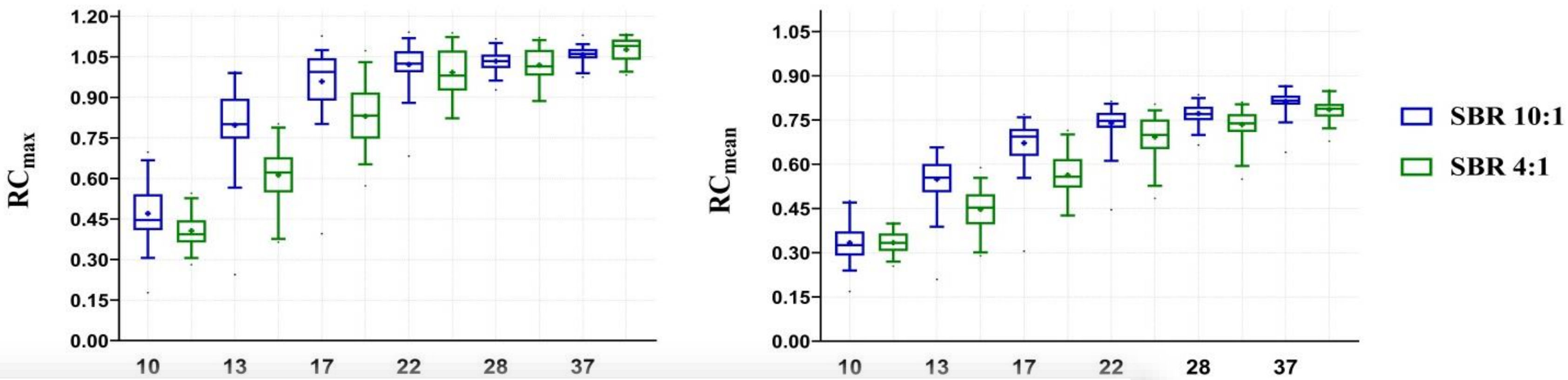
PMCID: PMC10102741 PMID: 37064407



Diameter (mm)	SBR 10:1				SBR 4:1			
	RC_{max}	RC_{mean}	RC_{peak}	RC_{10V}	RC_{max}	RC_{mean}	RC_{peak}	RC_{10V}
10	0.4-0.54	0.29-0.37	0.25-0.29	0.33-0.41	0.36-0.44	0.3-0.36	0.29-0.33	0.33-0.39
13	0.74-0.89	0.50-0.6	0.47-0.53	0.61-0.71	0.54-0.67	0.39-0.49	0.42-0.5	0.5-0.61
17	0.88-1.05	0.62-0.71	0.65-0.73	0.8-0.93	0.74-0.91	0.52-0.61	0.58-0.66	0.66-0.79
22	0.99-1.07	0.72-0.77	0.85-0.91	0.94 -1	0.92-1.07	0.65-0.75	0.79-0.88	0.88-0.99
28	1.01-1.06	0.74-0.79	0.91-0.98	0.97-1.04	0.98-1.08	0.71-0.77	0.88-0.96	0.95-1.04
37	1.04-1.08	0.8-0.83	0.94-0.99	1.01-1.05	1.04-1.11	0.76-0.8	0.91-1.03	1.01-1.09

Image reconstruction and AI

Kuang Gong , 2024, IEEE
Chi Qi , 2022, EJNMMI
Mohamed Abouhawwash , 2022, IEEE
Nicolas Aide , 2022, Seminars in Nuclear Medicine

- Direct reconstruction method from PET sinogram using supervised deep learning methods for denoising/reconstruction
- Developing AI-driven accurate WB FDG image quality using IQA-CCN
- propose a novel deep learning function (CNN) to estimate the goodness of image quality
- focus on TOF,PSF modelling, BPL algorithm, AI approaches

Commercial Options

SIEMENS Healthineers

- Reconstruction Algorithms:

3D-OSEM

TrueX (HD)

TrueX + TOF (ultra-HD)

- Scatter correction methods:

relative, absolute, WB relative, WB absolute

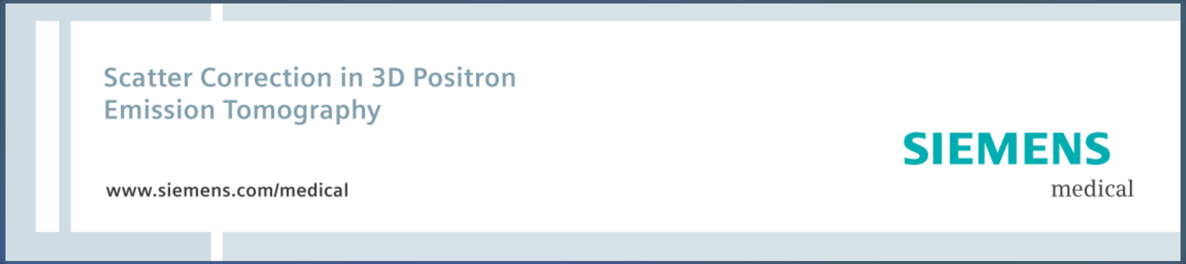
- Filters: Gaussian , Butterworth


Point Spread Function Reconstruction in PET

Michael E. Casey, Ph.D, Director of Physics, Siemens Molecular Imaging

www.siemens.com/mi

SIEMENS medical


Scatter Correction in 3D Positron Emission Tomography

www.siemens.com/medical

SIEMENS medical


White Paper

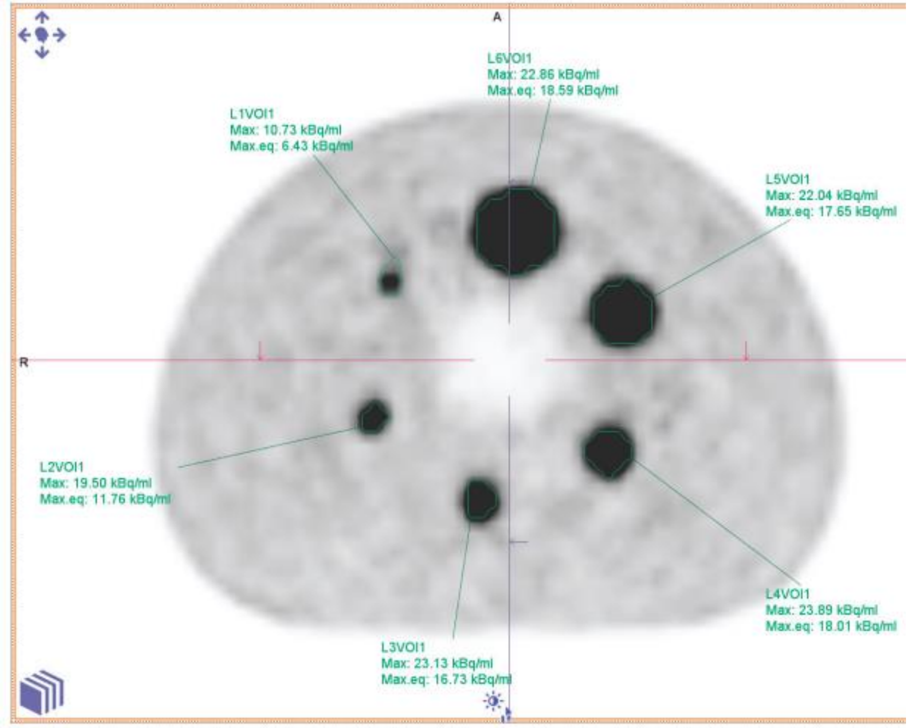
EQ•PET: Achieving NEMA-referenced SUV Across Technologies

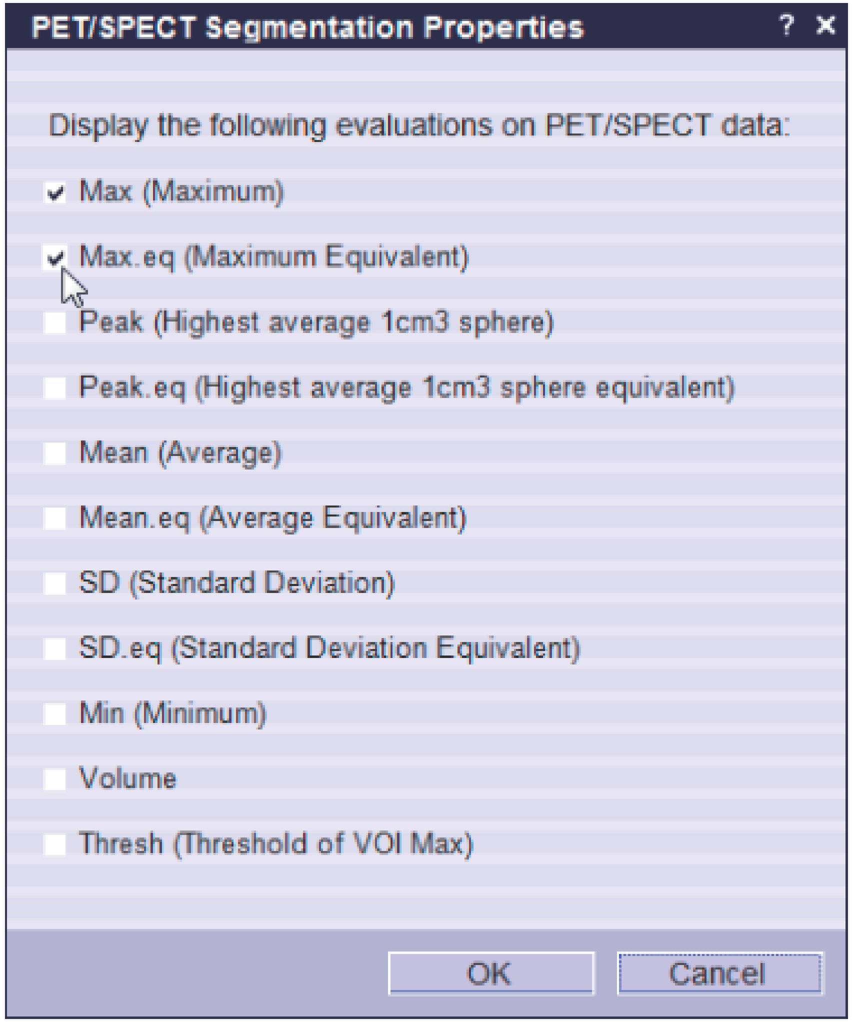
Matthew Kelly, PhD, Siemens Healthcare Sector

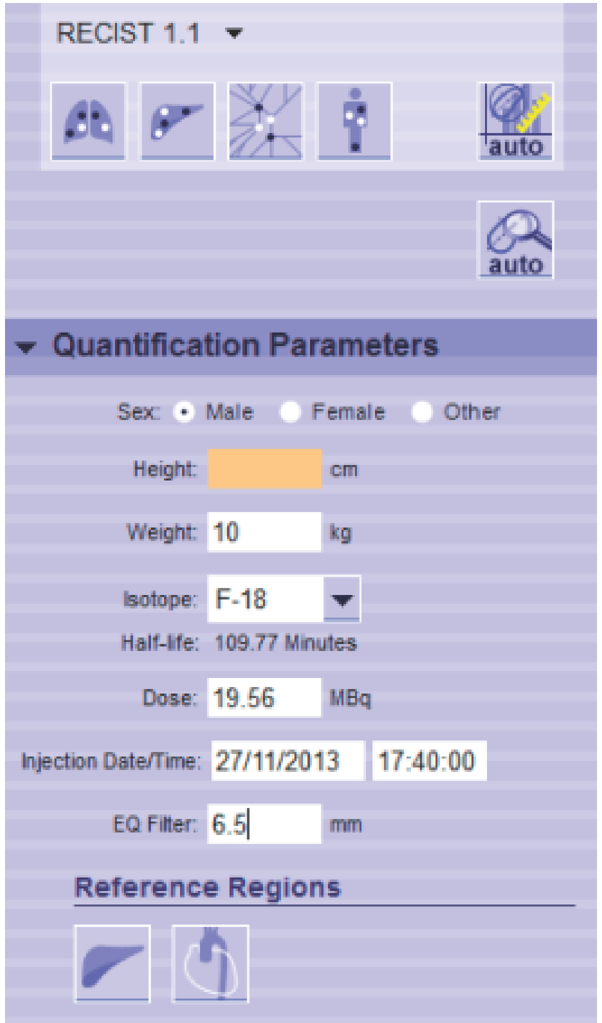
White Paper

EQ•PET: Achieving NEMA-referenced SUV Across Technologies

Matthew Kelly, PhD, Siemens Healthcare Sector







GE Healthcare

- **Reconstruction Algorithms:**

FORE-FBP (Fourier REbinning - Filtered Back Projection)

Filters: Hanning, Shepp-Logan, Rectangle, Butterworth

SharpIR

VUE Point HD (VPHD) – iterative/OSEM

VUE Point FX (VPFX) - use TOF

β

Q.Clear - full convergence while maintaining acceptable image quality , use Bayesian Penalized Likelihood (BPL) algorithm

PHILIPS Healthcare

- **Reconstruction Protocols:**

Body

Body-EARL

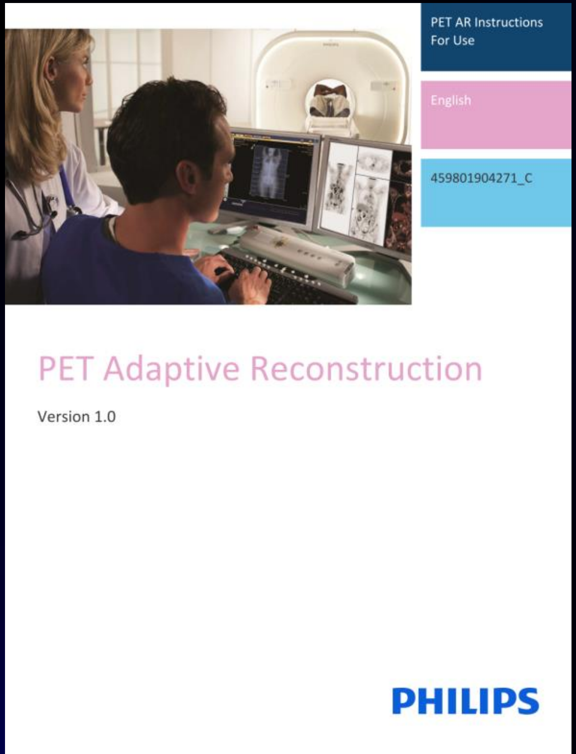
- Filters: Gaussian

Smooth/Sharp

Consists of four user-selectable Gaussian post-filter options with increasing levels of filtering/smoothing (as shown in the table below):

- Normal
- Smooth (default)
- SmoothA
- SmoothB

Filtering Options	Normal	Smooth (default)	SmoothA	SmoothB
FWHM (mm)	4	5	6	7



- **PSF (point spread function)**

Using Richardson-Lucy algorithm which is iterative.

For control of noise ➔ use regularization (Sieve-kernel (FWHM))

The default PSF parameters are:

- PSF Iterations = 1
- PSF Regularization = 6 mm

- **PET Adaptive Reconstruction**

Challenging Area

1. Correction Challenges

- Motion correction (especially for whole-body dynamic scans) is still very imperfect.
- Scatter correction is never 100% accurate. Especially in low-count regions, or at edges (lung/liver interfaces, for example), scatter estimation errors propagate badly.
- Attenuation correction errors from CT mismatches or MR-based estimation (in PET/MR) are still a big source of bias.
- Partial volume correction (PVE correction) remains an issue, especially for very small lesions.

2. Reconstruction Algorithm Development

- Time-of-Flight (TOF) integration is strong now, but there are opportunities to push TOF resolution better or exploit it more cleverly.
- Regularization (penalizing noise without blurring detail) — finding new priors for MAP (maximum a posteriori) reconstruction is an active area.
- Ultra-fast reconstruction using deep learning is popular but still faces issues with generalization and trust (artifact hallucination risk).

3. AI/Deep Learning Application

- End-to-end learned reconstruction (e.g., skipping traditional iterative reconstruction and letting a network learn it all) is promising but unstable and risky for clinical trust.
- Physics-informed neural networks — networks that respect PET physics rather than just doing black-box prediction — are a growing but challenging field.
- Low-count PET reconstruction (e.g., 1% of standard dose) with deep learning denoising or reconstruction is very active but still not perfect.
- Uncertainty quantification — AI reconstructions often look good, but how do you know if a result is reliable? This is a hot topic.

4. Novel Applications/Problems

- Dynamic PET reconstruction (parametric imaging) harder and often still relies on simplifying assumptions (like simple kinetic models). New models, AI acceleration for parametric imaging, or better noise handling could be huge.
- Total-body PET (like the EXPLORER scanner) opens new reconstruction challenges because of enormous data volume and new motion patterns.
- Multi-tracer PET (imaging two tracers at once) needs very sophisticated reconstruction algorithms to untangle signals.

Hot topics in 2025

Rank	Topic	Novelty (2025)	Practical Impact
1	Uncertainty Maps for AI-Reconstructed PET	★★★★★	★★★★☆
2	AI-Enhanced Scatter Correction	★★★★☆	★★★★★
3	Parametric PET Imaging Acceleration	★★★☆☆	★★★★★
4	Motion Correction Whole-Body PET	★★★☆☆	★★★★★
5	Low-Dose AI PET Reconstruction	★★☆☆☆	★★★★☆
6	Total-Body PET Fast Reconstruction	★★★★☆	★★☆☆☆ (if no data access)

Thank you