Image reconstruction for the Walk-Through PET system

Jens Maebe

GHENT UNIVERSITY

WT PET

THE FAST LANE

Belgium

Costa Rica

My background

- Engineering Physics at Ghent University

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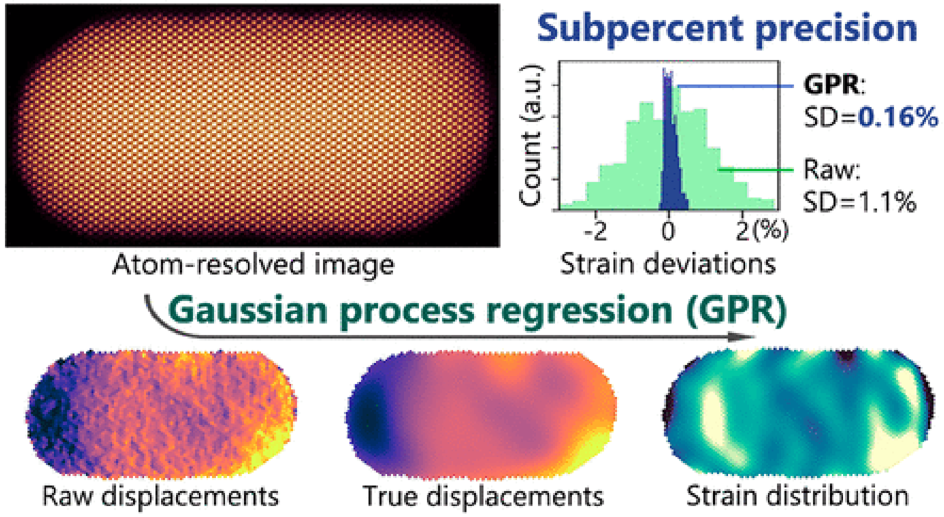
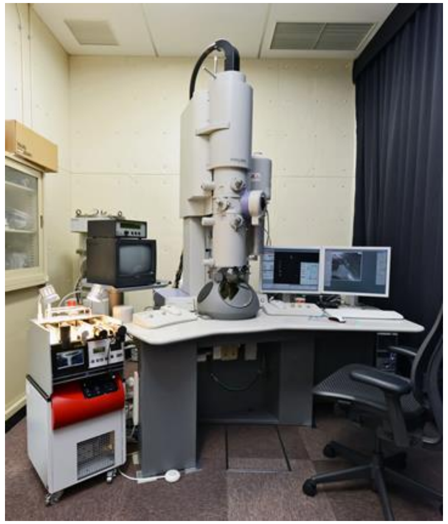
- Engineering Physics at Ghent University
- Master thesis at Kyushu University
  - Molecular dynamics and (S)TEM to study nanoparticles





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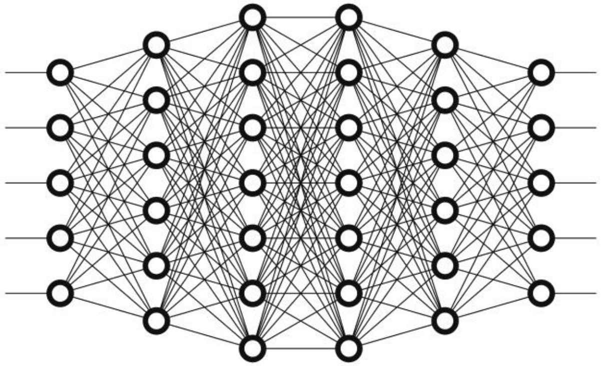
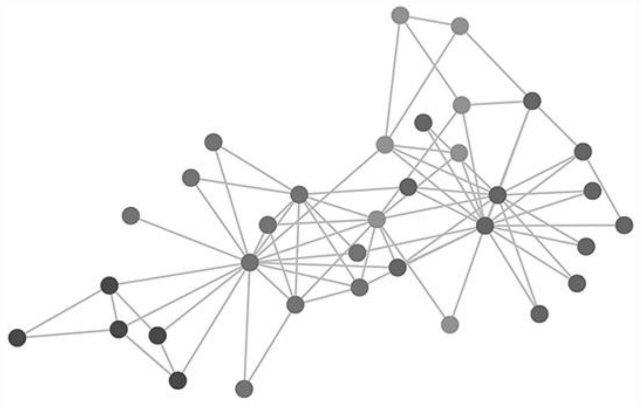
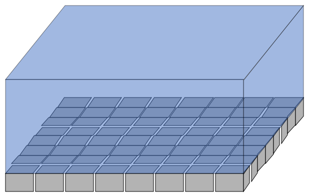
- Data Science consultant at Devoteam
  - Fraud detection with deep learning and graph theory

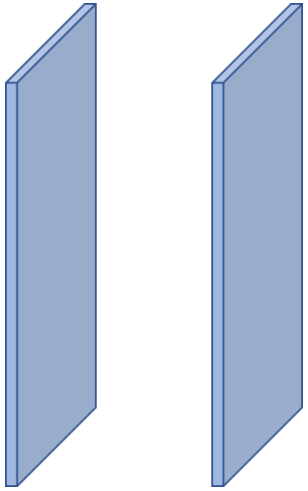




My background

- Engineering Physics at Ghent University
- Master thesis at Kyushu University
  - Molecular dynamics and (S)TEM to study nanoparticles
- Data Science consultant at Devoteam
  - Fraud detection with deep learning and graph theory
- PhD at Ghent University
  - Time of flight in monolithic PET detectors
  - Image reconstruction for the WT-PET



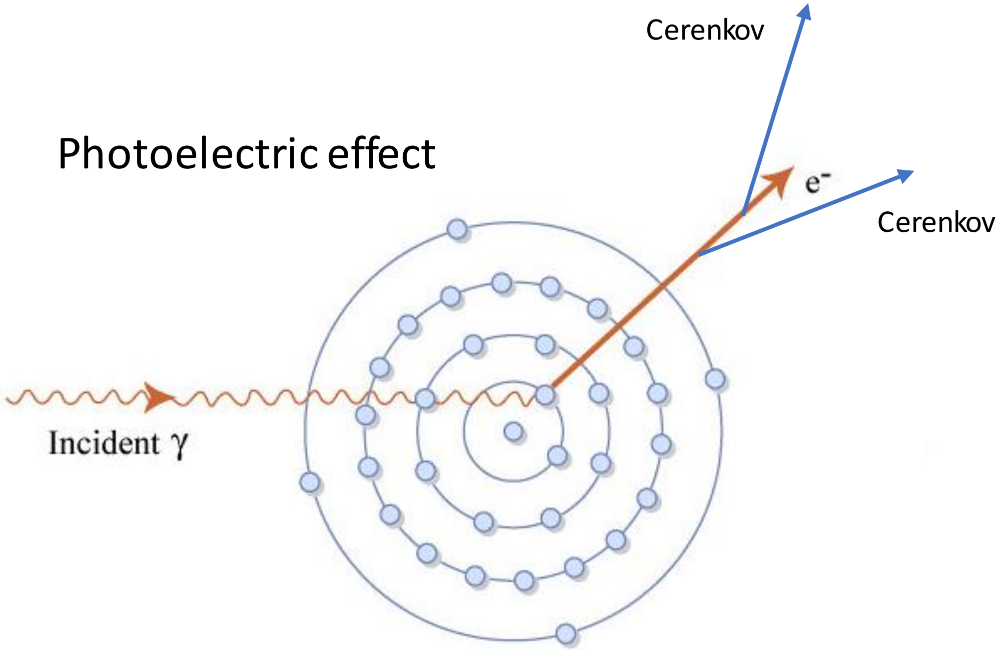


Cerenkov in monolithic BGO

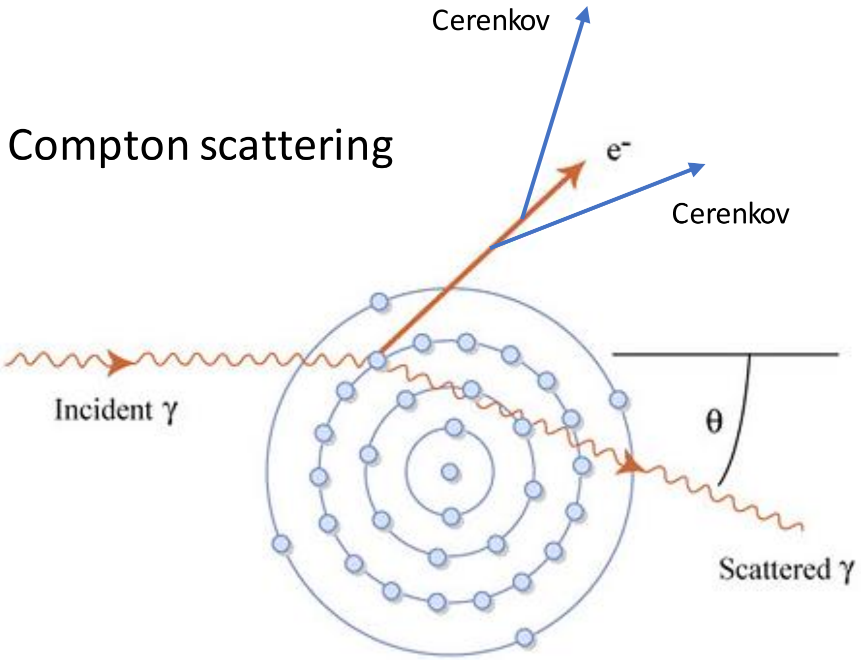
A simulation study in GATE

Cerenkov emission

Photoelectric effect

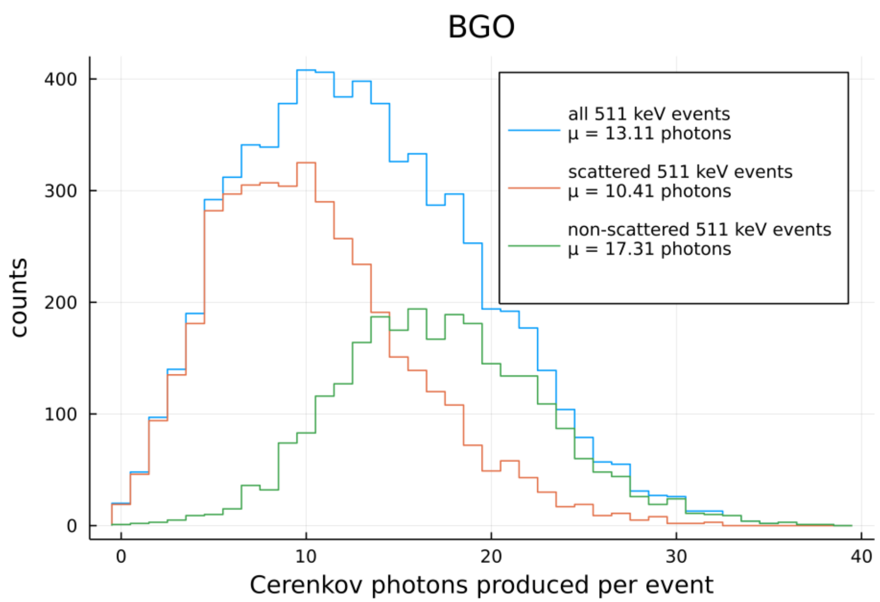


Compton scattering



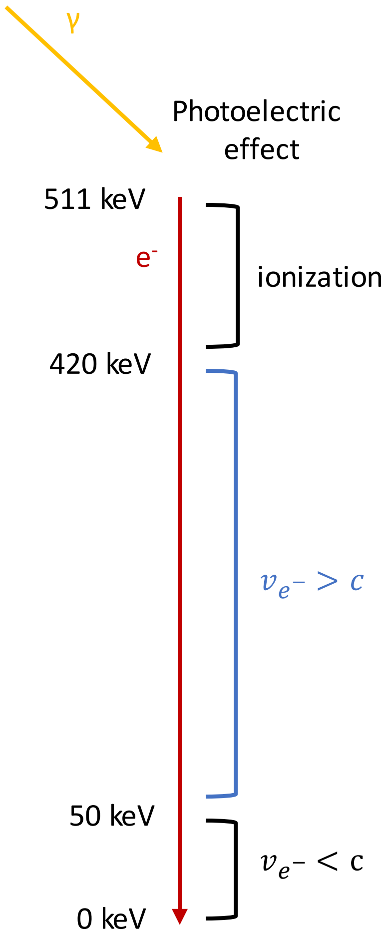
Figures from: https://ocw.mit.edu/courses/12-091-medical-geology-geochemistry-an-exposure-january-iap-2006/

Cerenkov emission

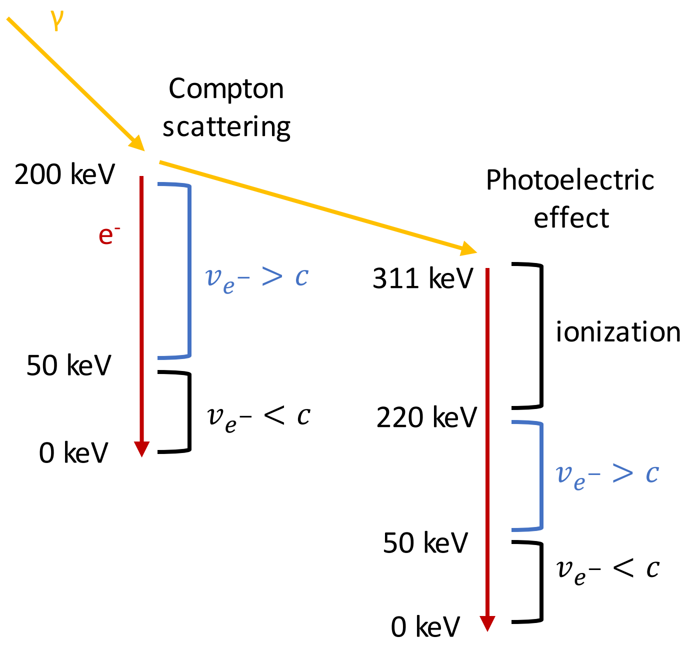


	# Cerenkov photons
Compton scattered	10
Purely photoelectric	17
Average	13

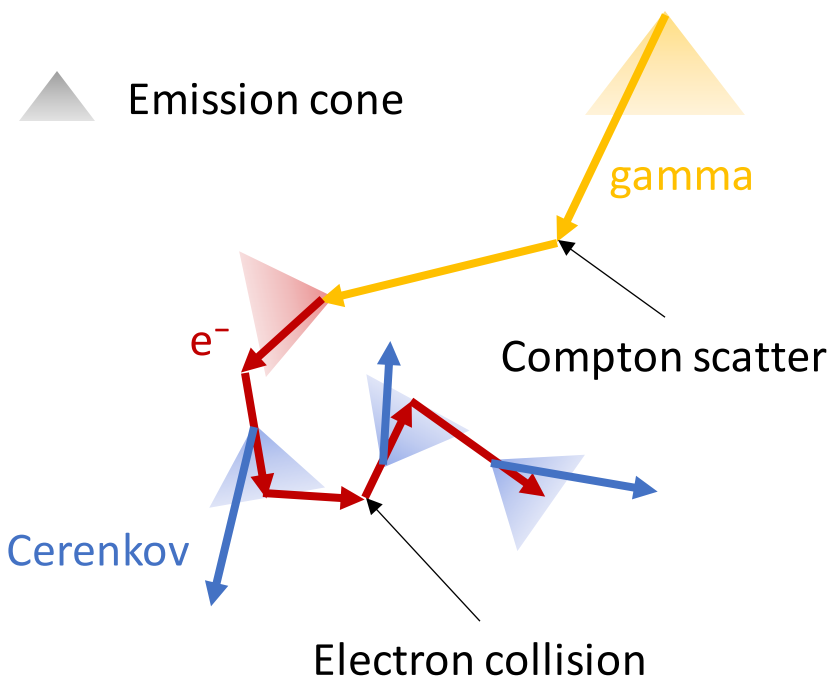
Compton scattered

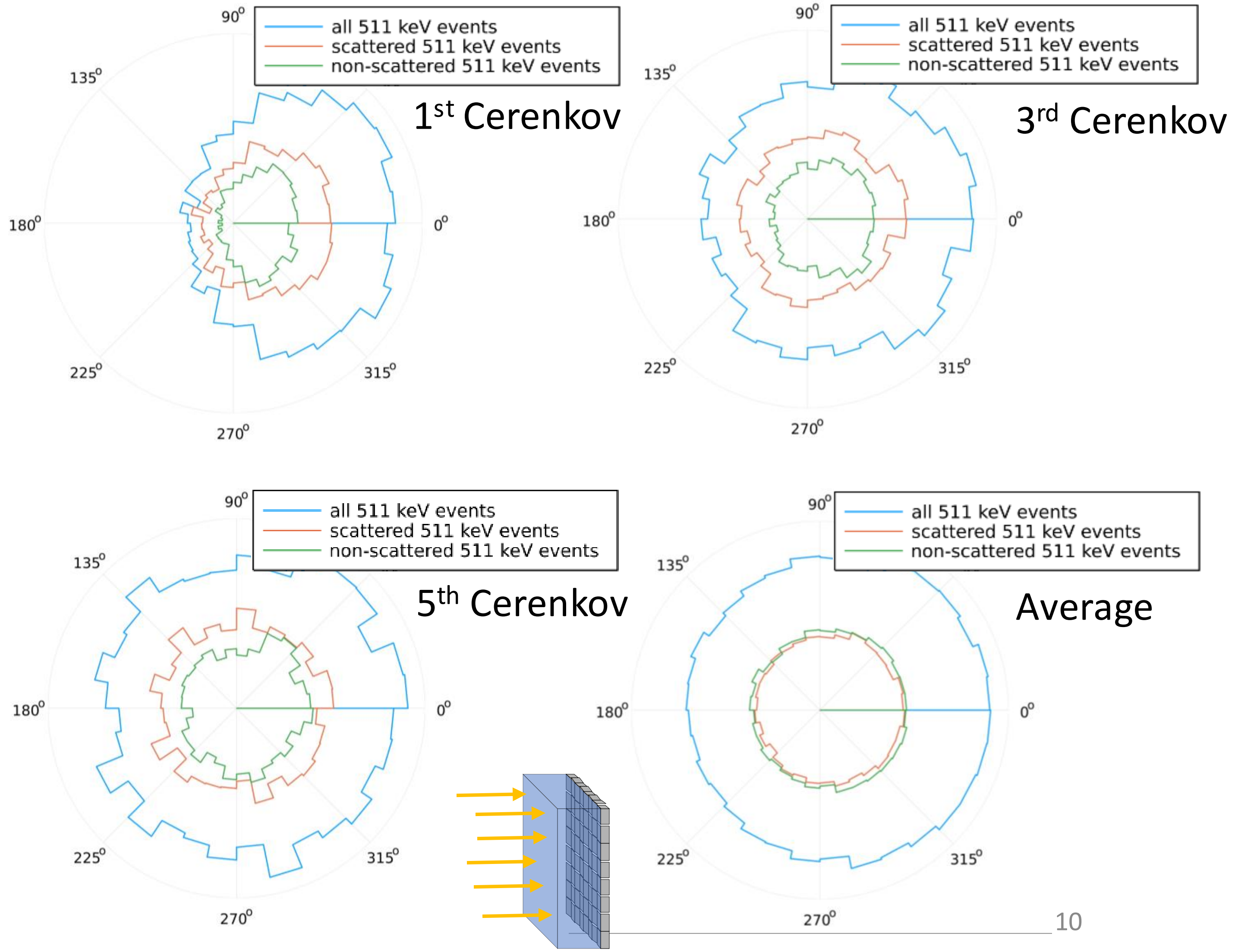


Purely photoelectric

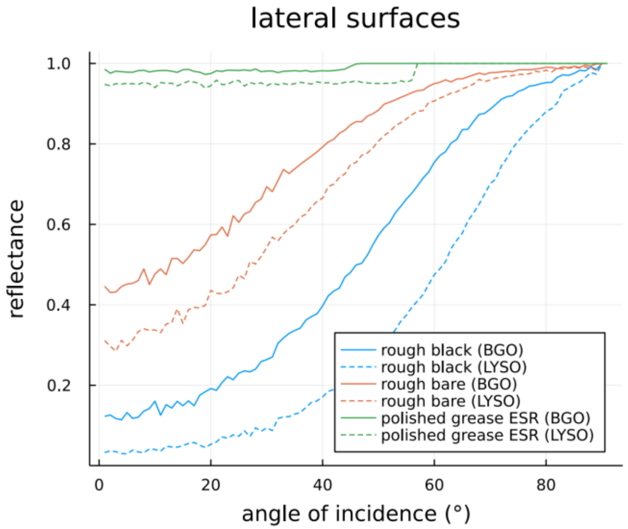


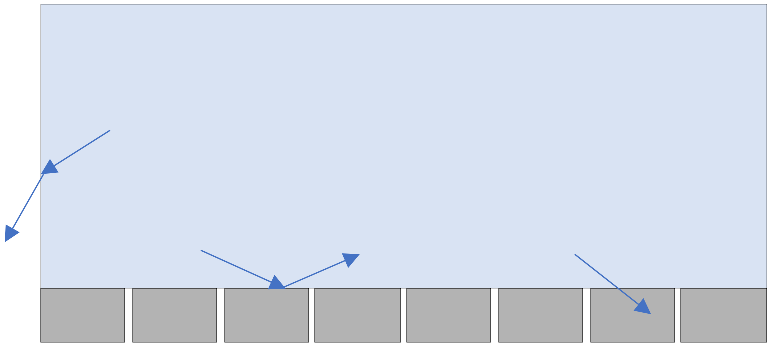
Cerenkov emission

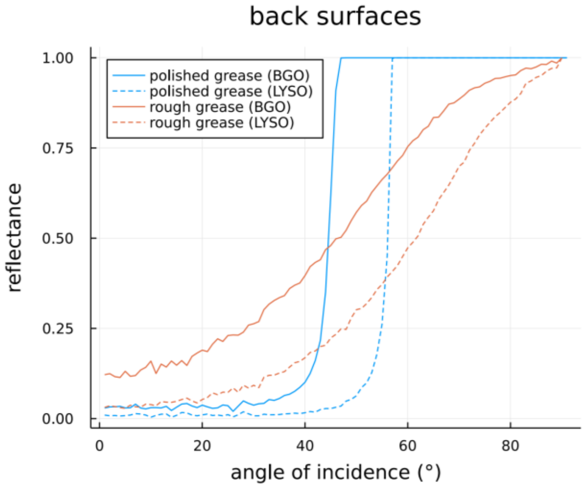


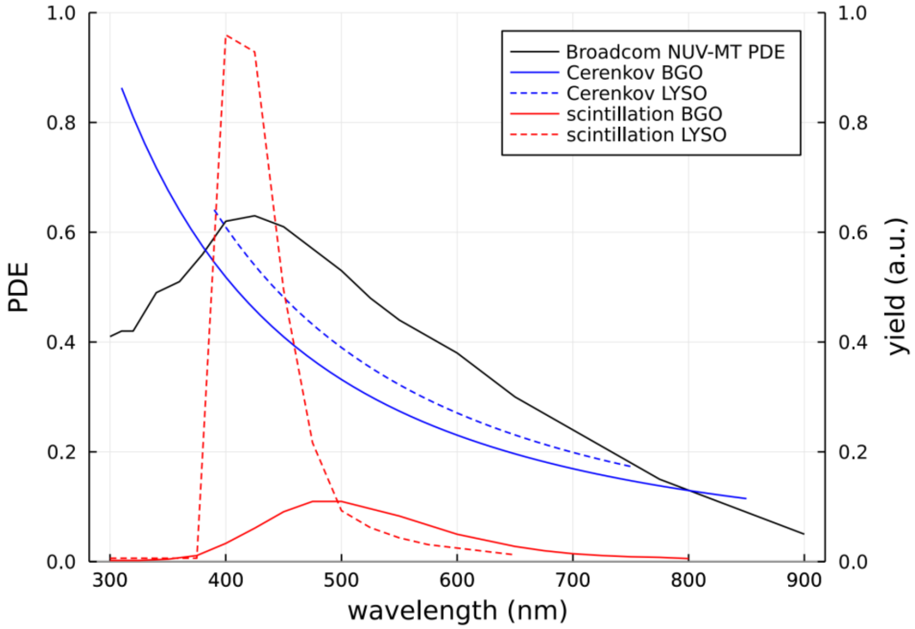


Cerenkov detection

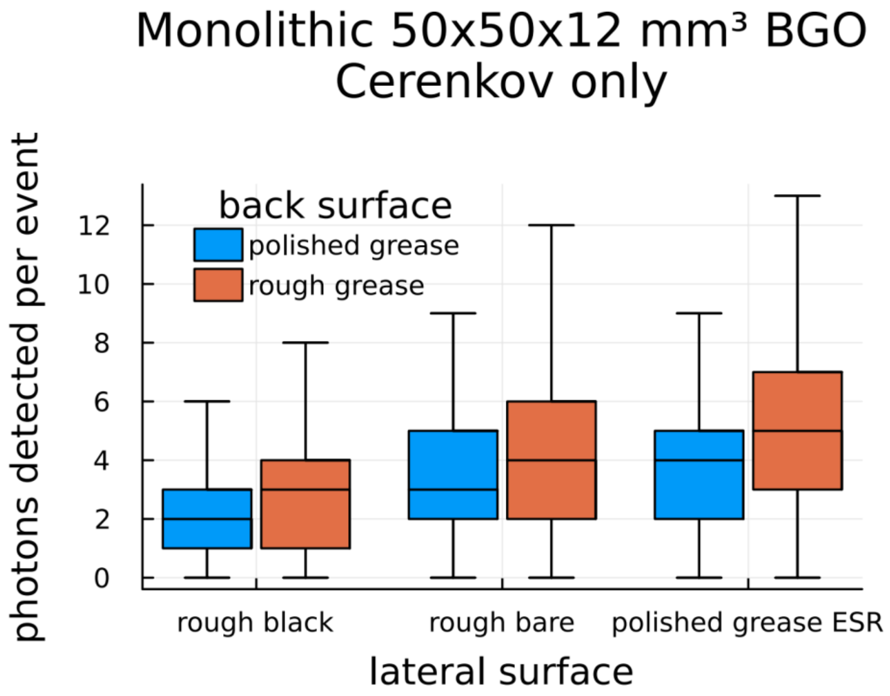








Cerenkov detection



Spread out over 8x8 (64) SiPMs

→ Unlikely to detect > 1 Cerenkov photons per SiPM

→ Requires triggering below the single photoelectron level

The Walk-Through PET

A flat panel LAFOV PET design based on monolithic detectors

The team in Belgium

Stefaan Vandenberghe

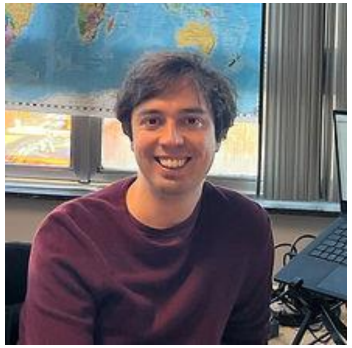
Christian Vanhove

Nadia Withofs

Florence Muller

Maya Abi Akl

Meysam Dadgar



Jens Maebe

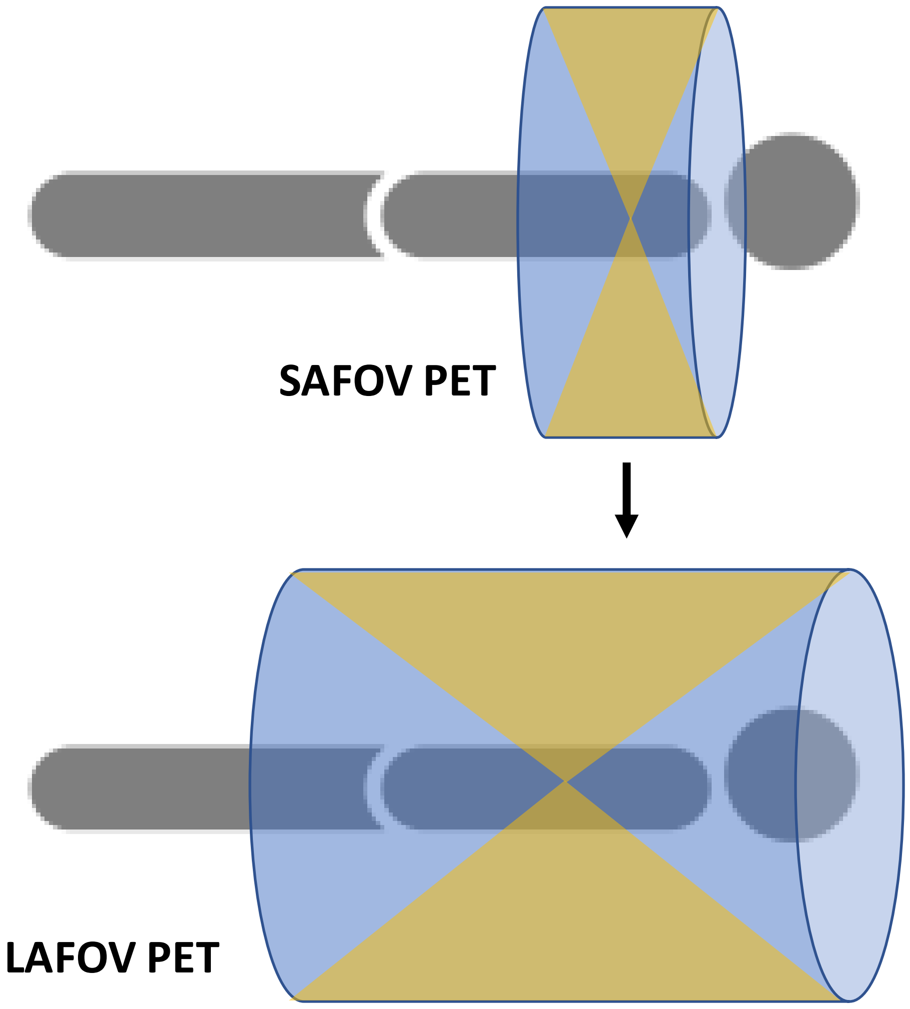
Boris Vervenne

Outline

- Design and current state
- NEMA system characterization
- Image reconstruction
- Remaining challenges
  - Limited angle artefacts
  - CT-less attenuation correction
- XCAT lesion detectability

Design and current state

Total-Body PET



Increased sensitivity
- Better image quality
- Lower dose scans
- Shorter scans

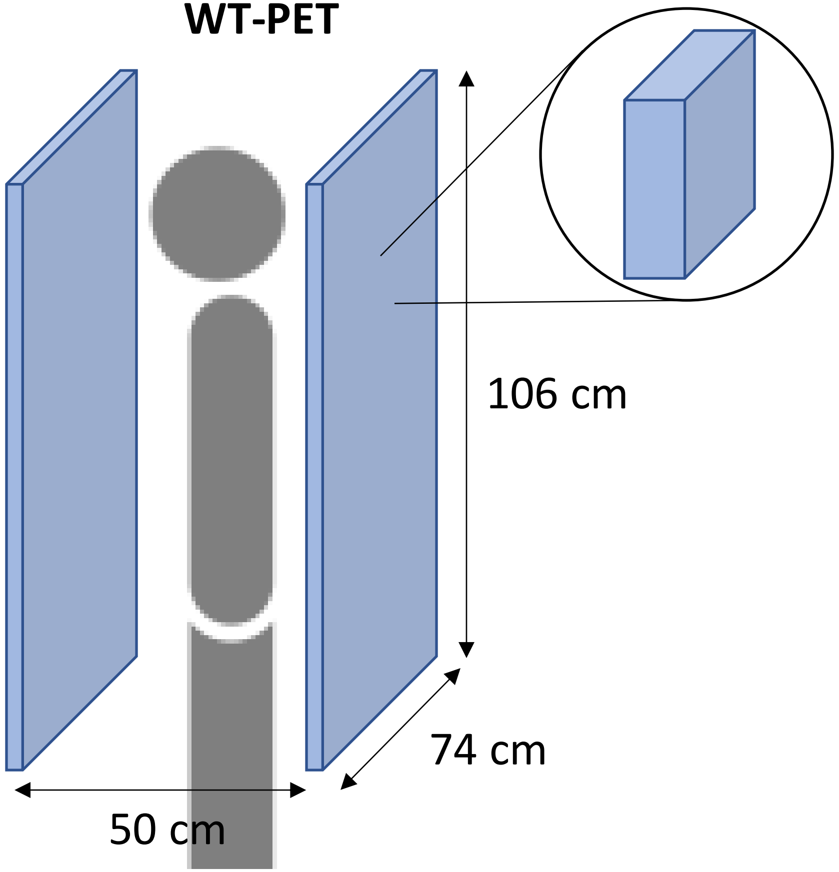
Single bed position scanning
- Dynamic imaging

Increased system cost
- Fixed costs: CT, data/reconstruction server, …
- Scales linearly with AFOV: scintillators, SiPMs, electronics

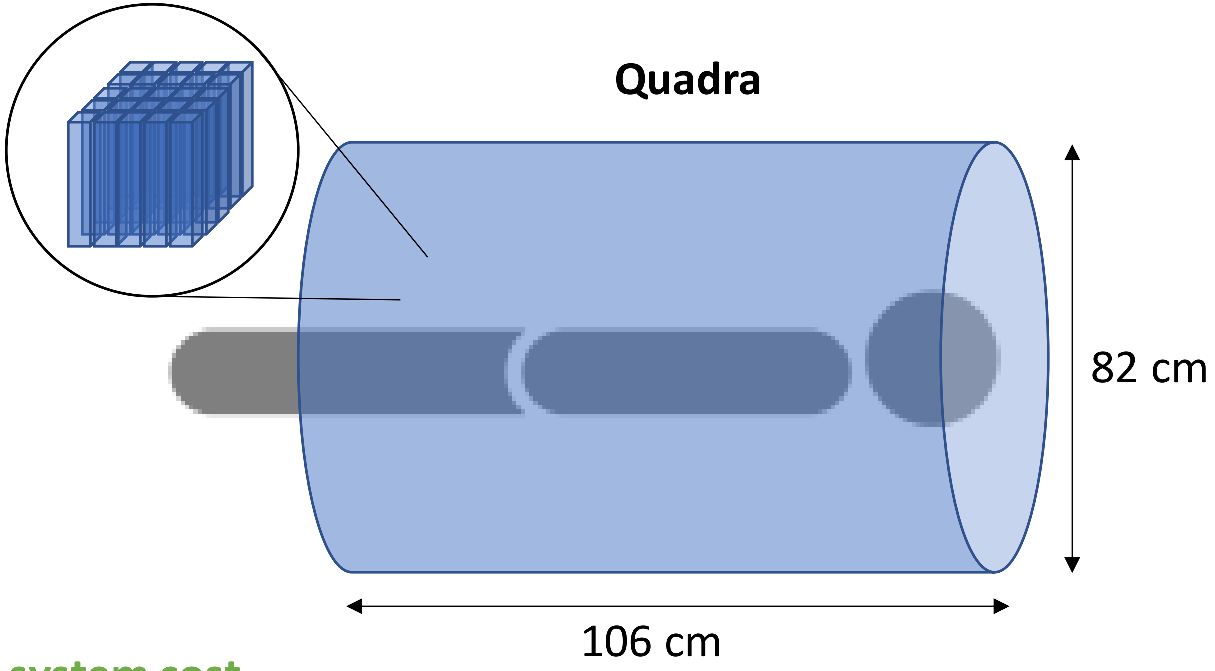
Patient throughput remains limited
- Sub one-minute scans become possible
  → patient preparation becomes limiting factor

Walk-Through PET

WT-PET



Quadra



Dimensions based on CT-scans from PET patients
106 cm AFOV: simultaneous head + torso imaging

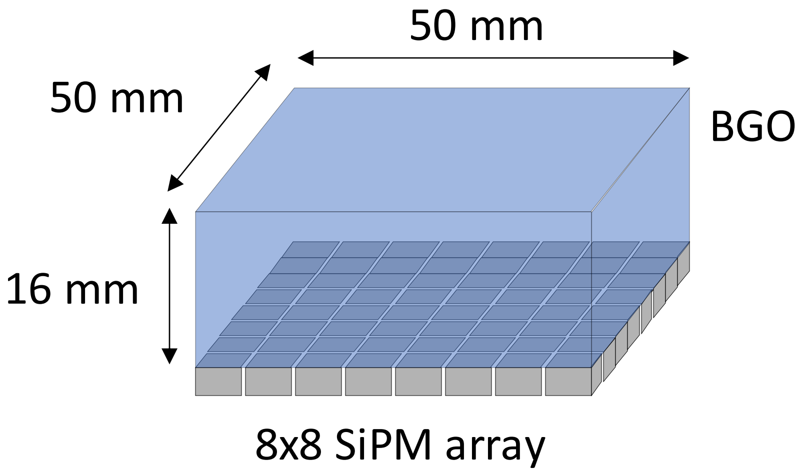
Reduced system cost

- Decreased detector coverage (≈ 1/2)
- Use of monolithic detectors
- BGO scintillators

Increased patient throughput

- Aiming for 30 s acquisitions

Monolithic detectors



*

Spatial resolution:
- 2D: 1.3 mm
- DOI: 2 mm

TOF resolution:
- 327 / 400 ps

Energy resolution:
- 15 %

Maximum countrates:
- 1 Mcps
- 370 ns deadtime

*Based on experimental results from Pisa

Current state

GHENT UNIVERSITY

- Fundamental system/detector design
- Simulations for system characterization
- Software development

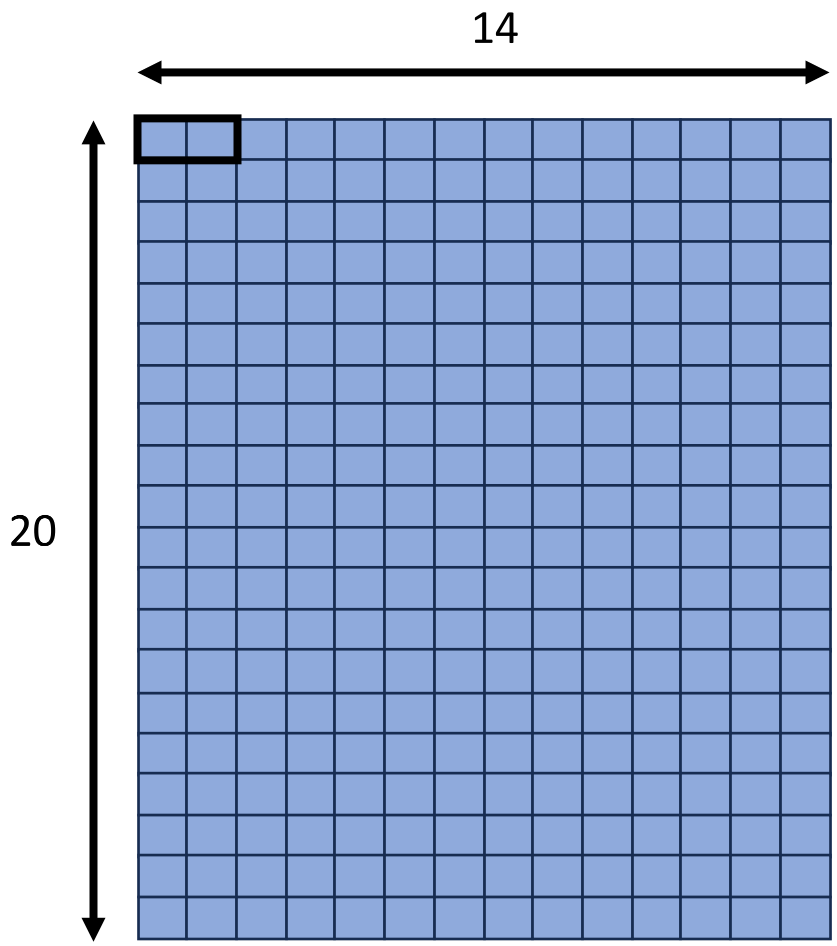
COMATE Engineering & Design

- System integration (electronics, mechanical)
- Cooling system
- End-user usability

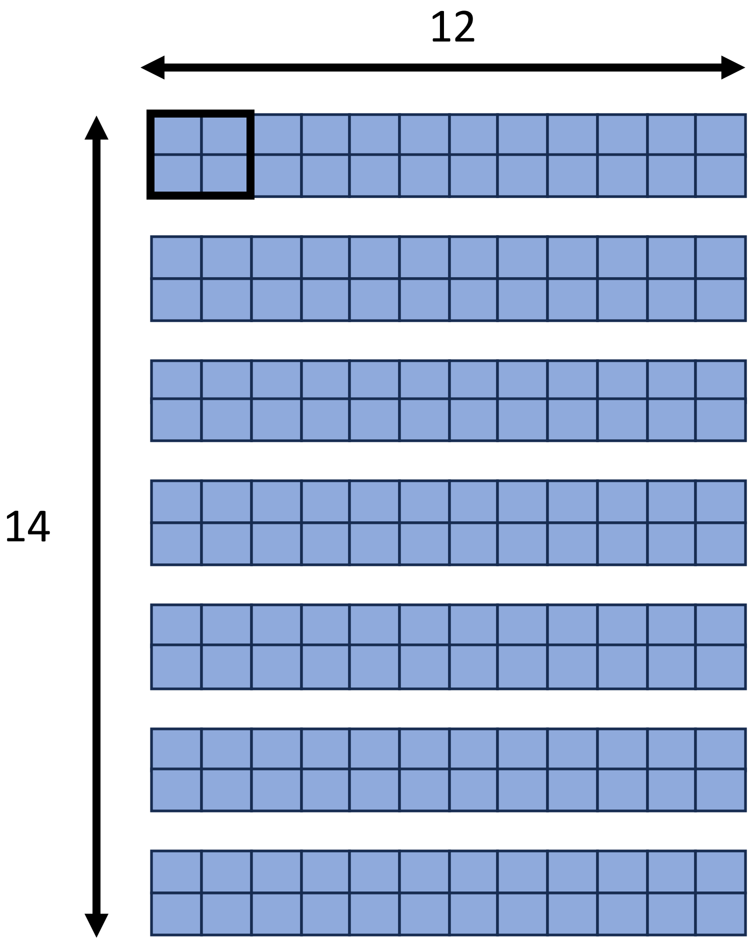
10 years PETsys Electronics

- Provides the electronic readout: TOFPET2 ASIC

Sparse LYSO configuration

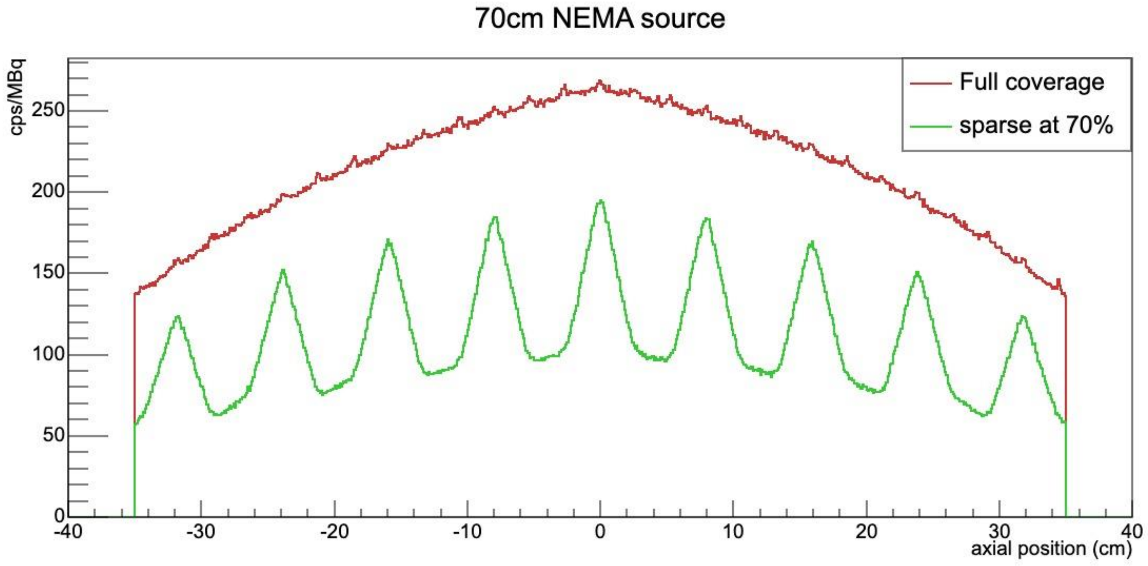


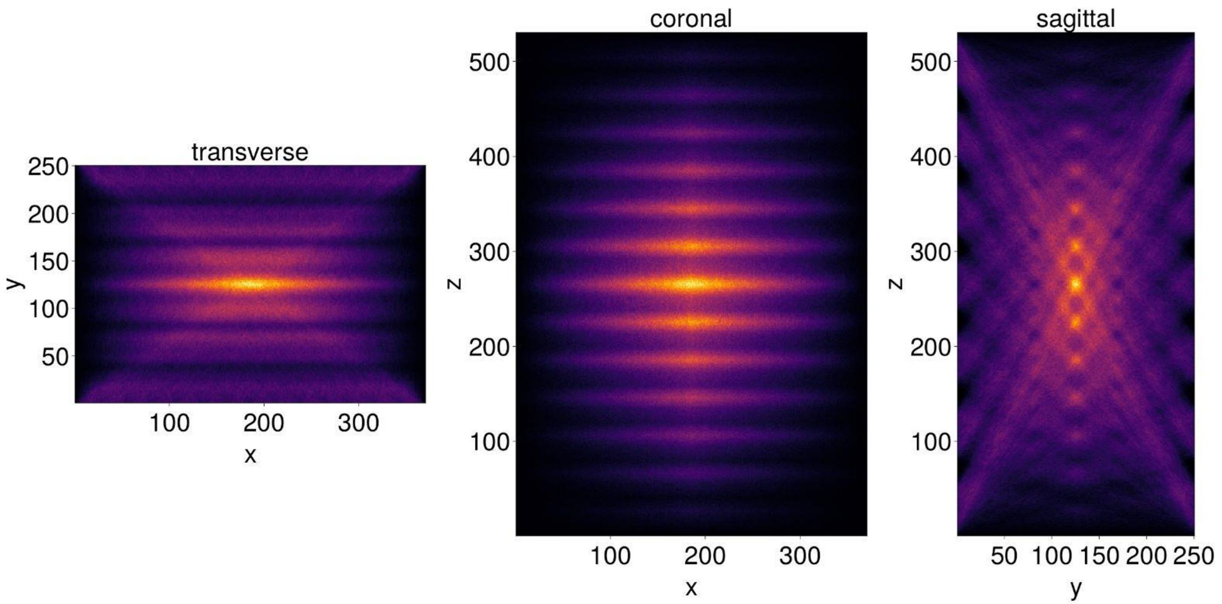
Pisa, BGO



PETsys, LYSO

Sparse LYSO configuration





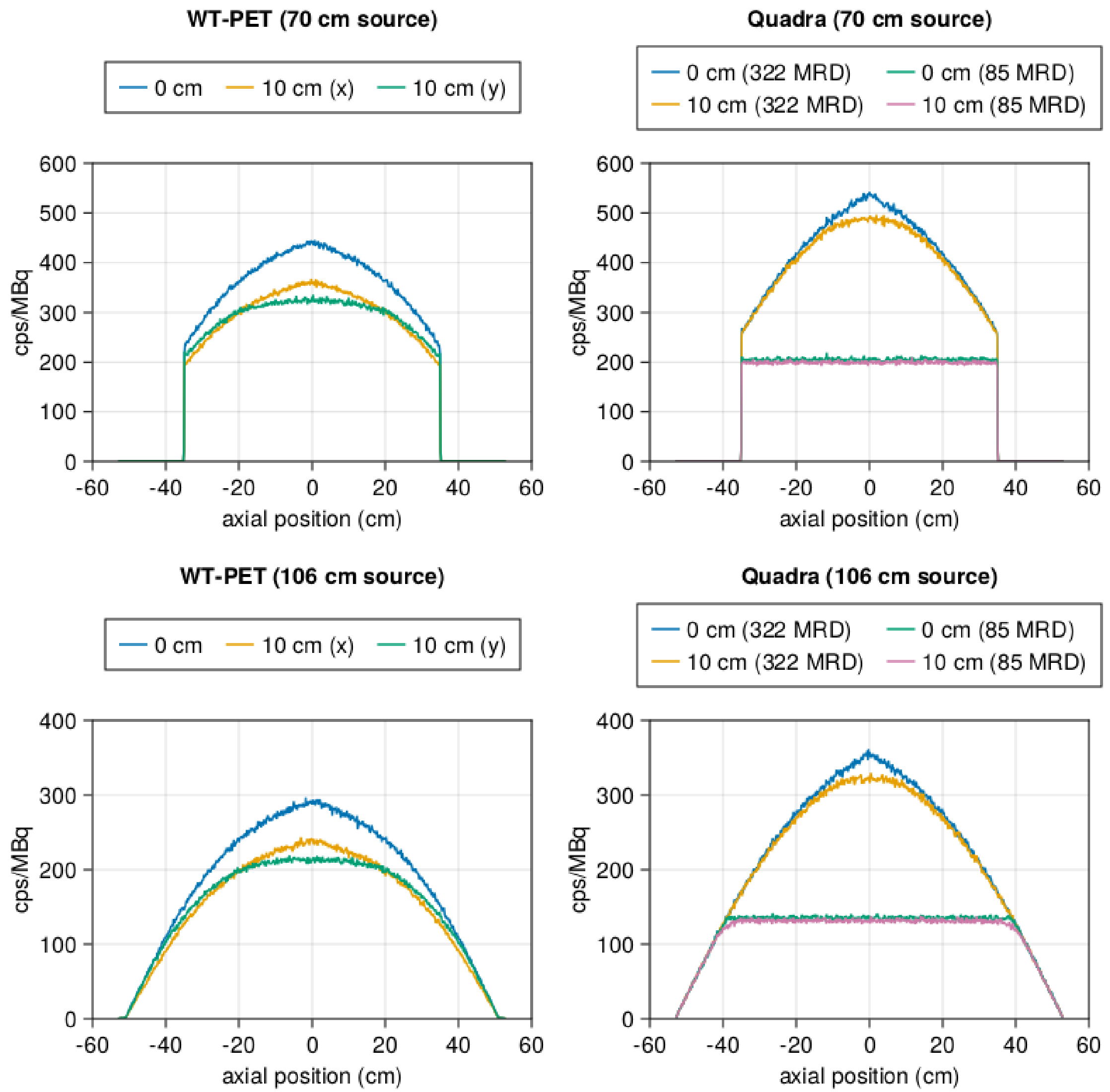
	Centered	Off center at X = 10cm	Off center at Y = 10cm
Sensitivity (kcps/MBq) **Full detector coverage**	150	121	117
Sensitivity (kcps/MBq) **Sparse 70% coverage**	77	63	60

NEMA system characterization

A comparison with Quadra based on GATE simulations

NEMA system characterization

Sensitivity



70 cm source (center)	Sensitivity (simulated) cps/kBq	Sensitivity (experimental) cps/kBq
WT-PET	154.0	-
Quadra (MRD 85)	87.0	82.6
Quadra (MRD 322)	179.7	175.3

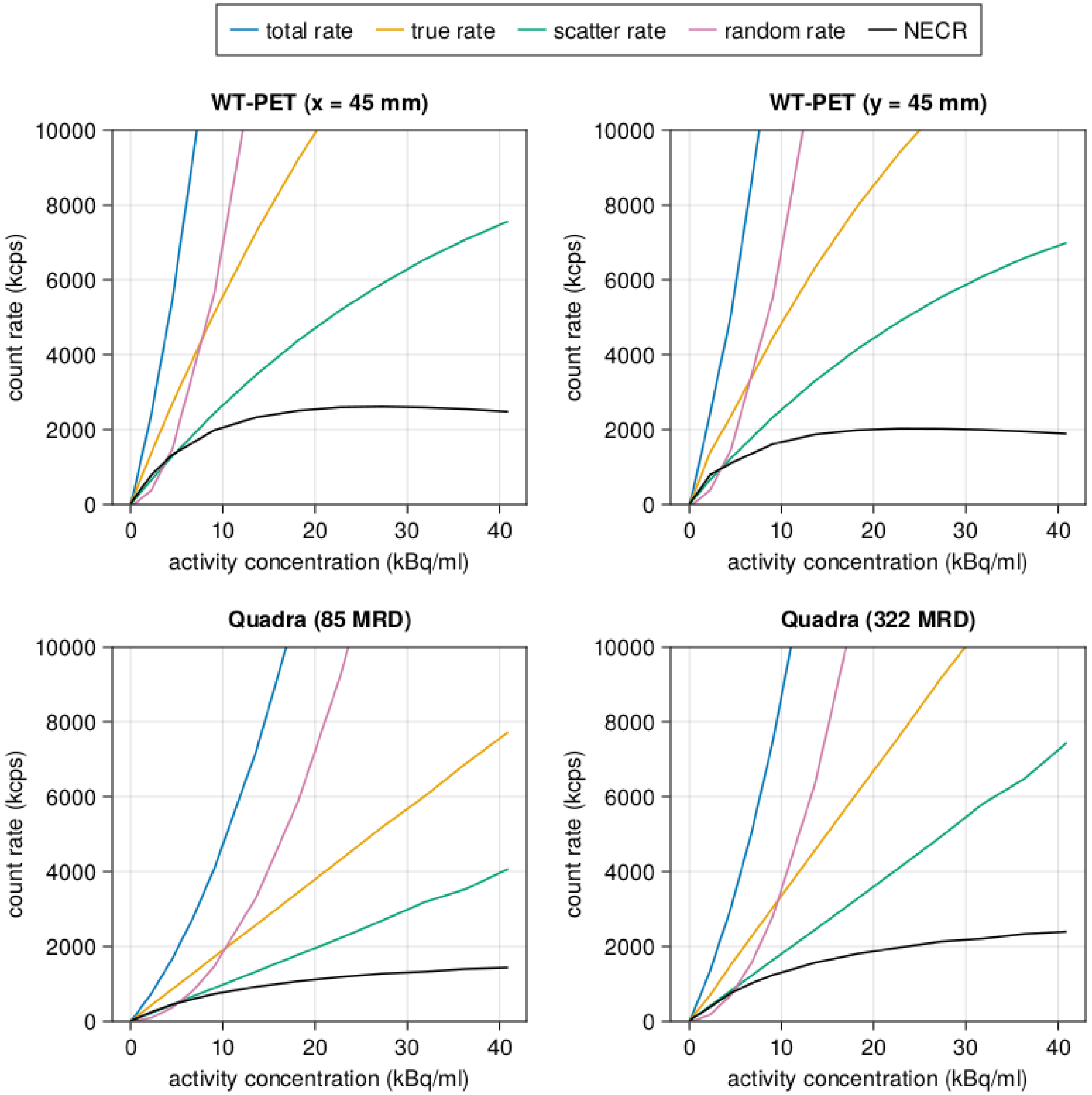
Scatter fraction

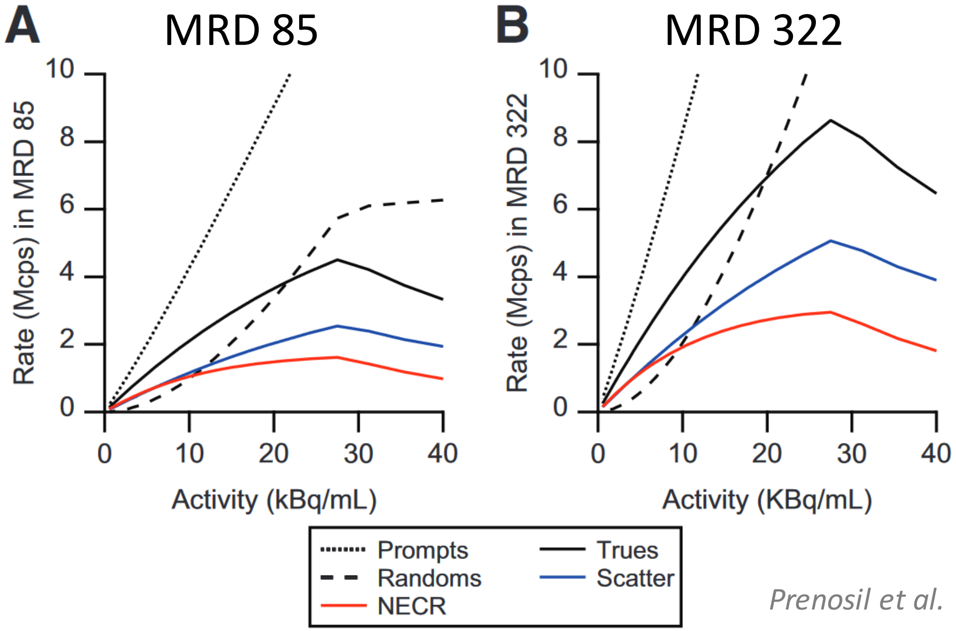
	Simulated	Experimental
WT-PET (offset along panels)	30.72 %	
WT-PET (offset towards panels)	29.58 %	
Quadra (MRD 85)	34.80 %	36 %
Quadra (MRD 322)	36.18 %	37 %

Includes patient bed

NEMA system characterization

Count rates



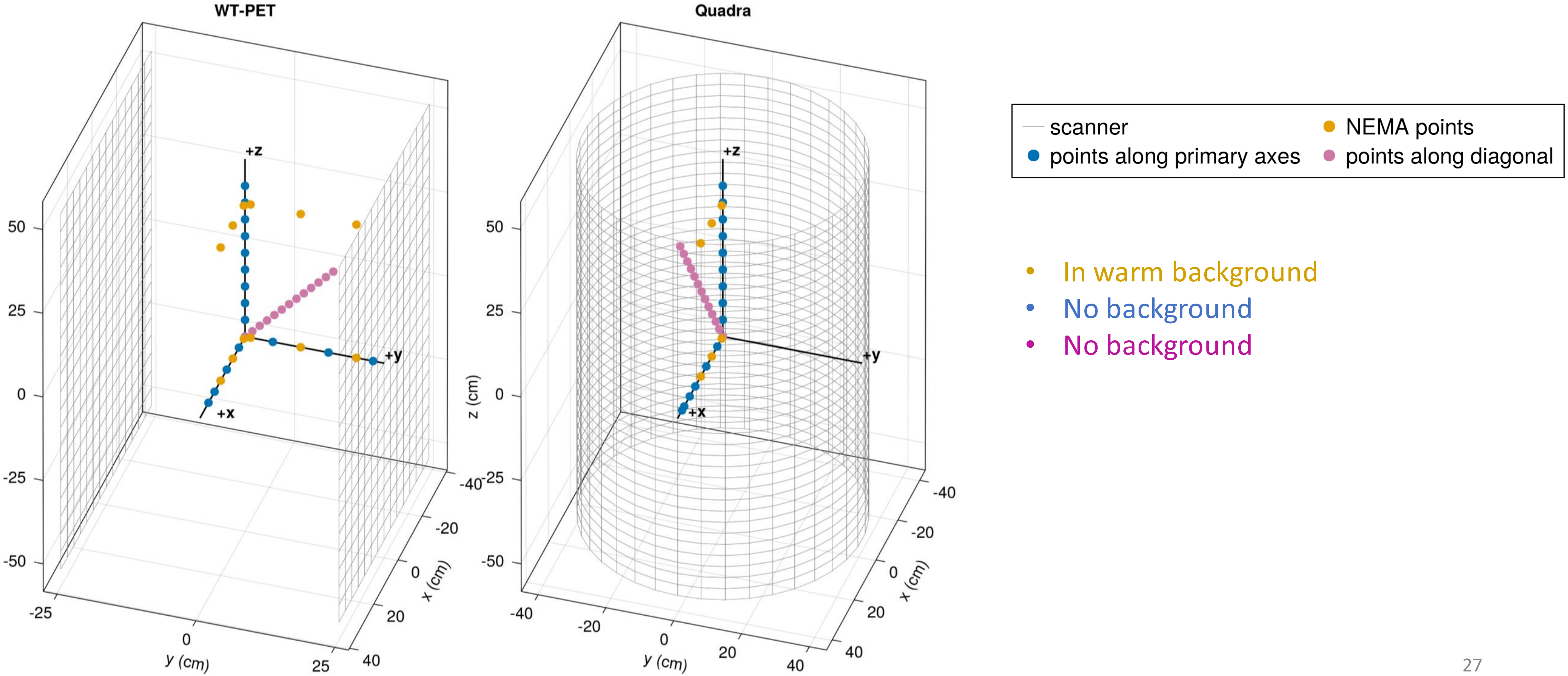


Prenosil et al.

GATE settings:

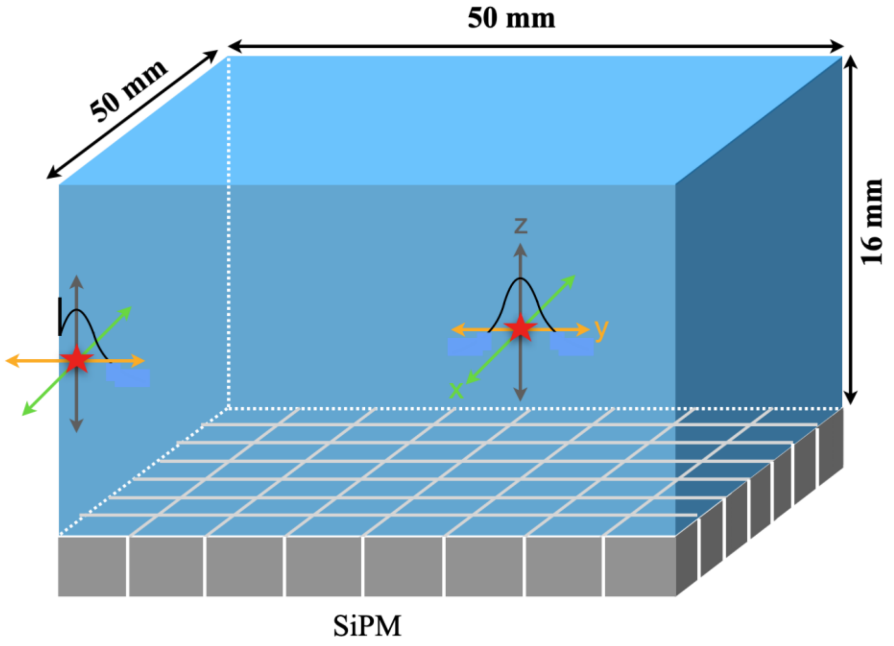
- Coincidence sorter: allPulseOpenCoincGate
- Multiples policy: takeAllGoods

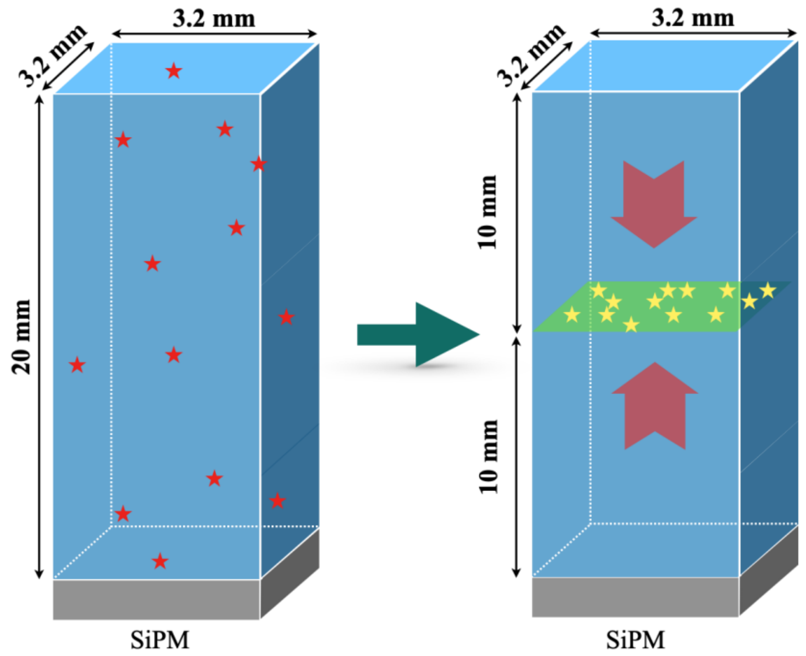
Spatial resolution



- In warm background
- No background
- No background

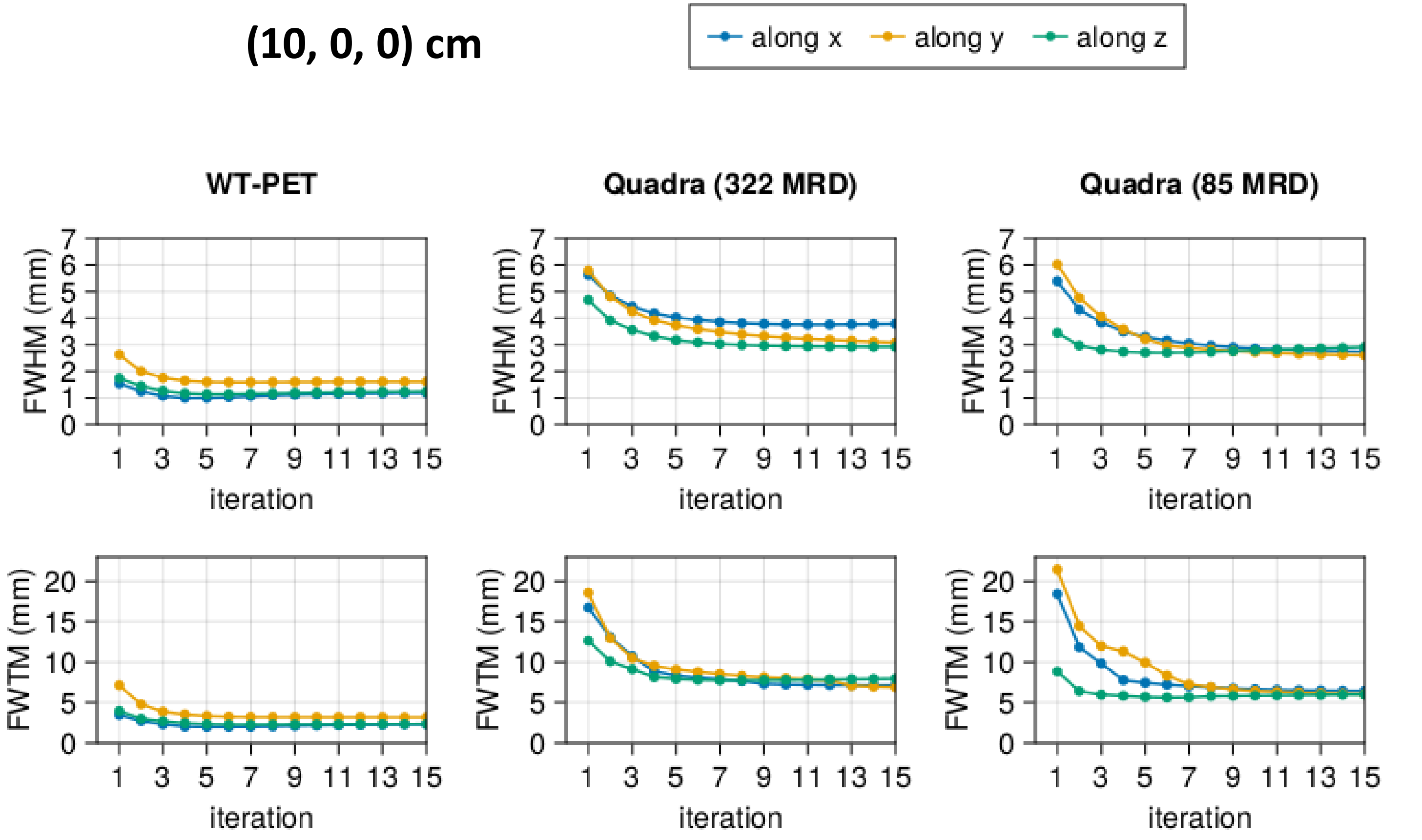
Spatial resolution: detector smearing

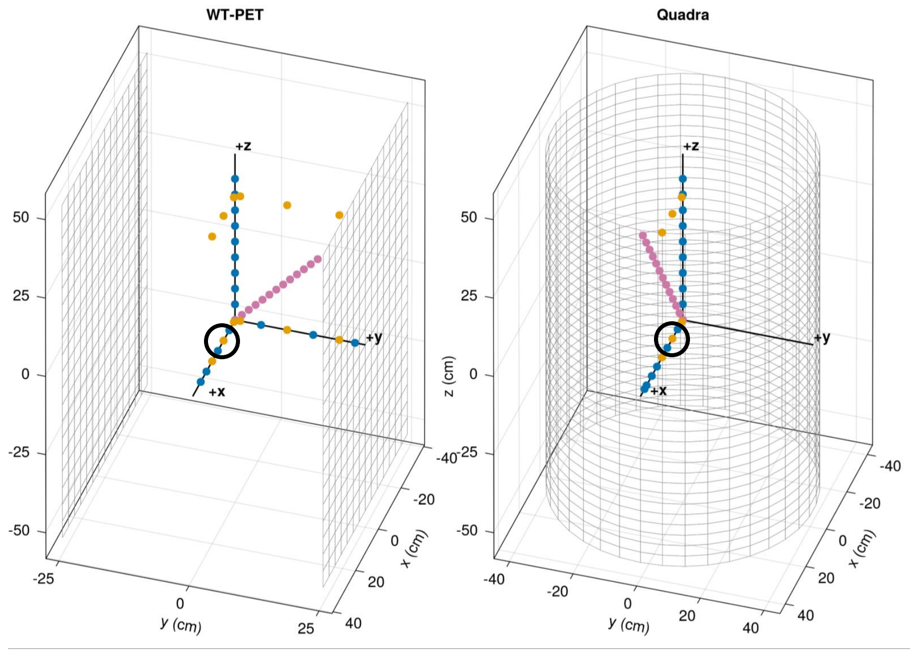




Spatial resolution

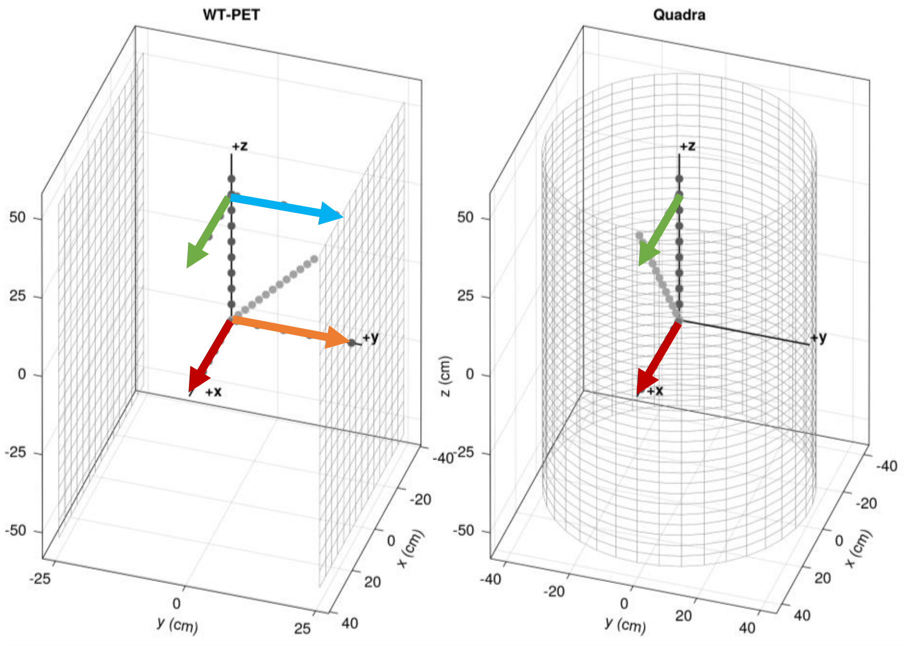
(10, 0, 0) cm





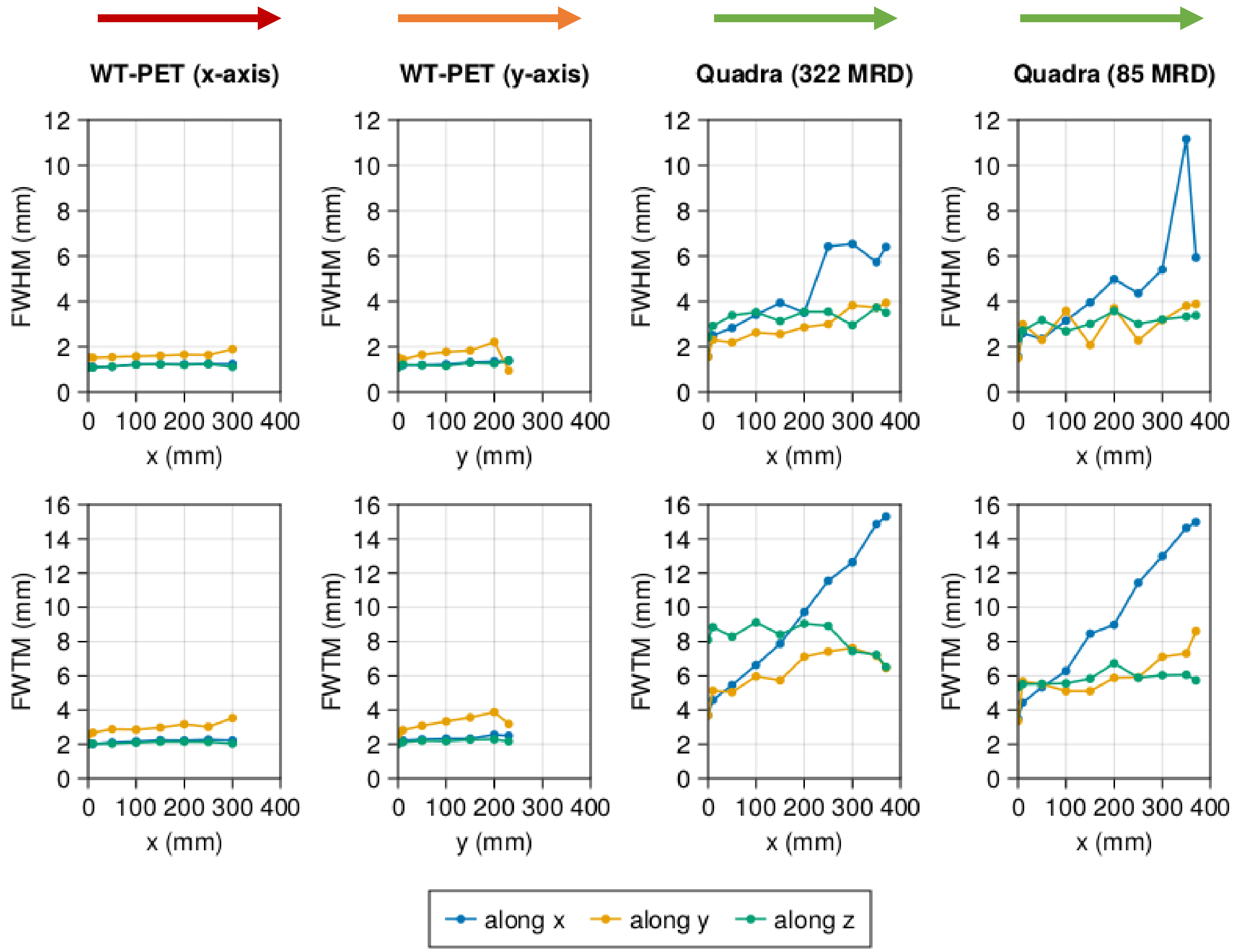
Spatial resolution: NEMA point sources

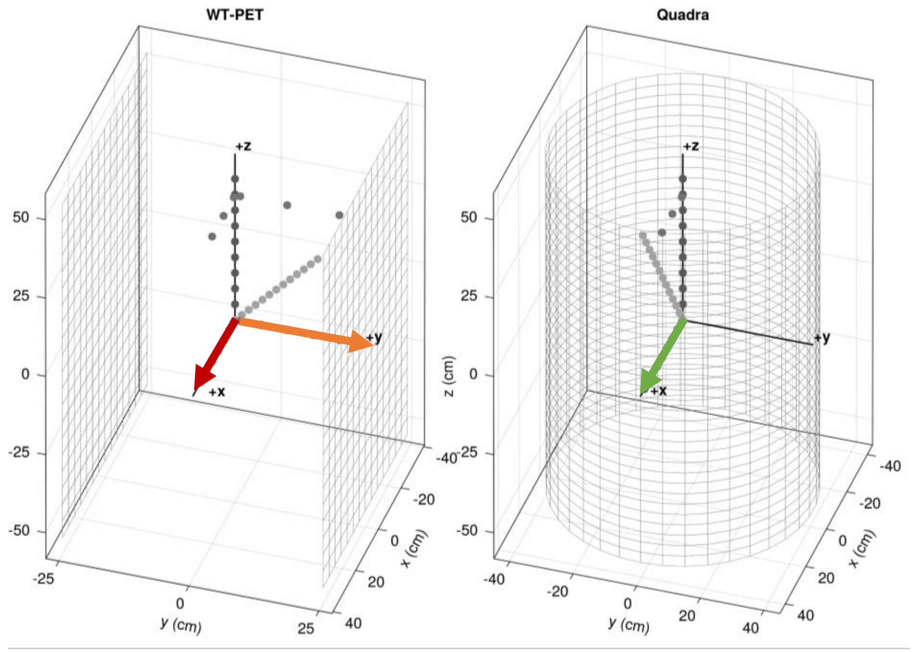
Scanner	Source Position (cm)		FWHM (mm) x	FWHM (mm) y	FWHM (mm) z	FWTM (mm) x	FWTM (mm) y	FWTM (mm) z
WT-PET	Center	(1, 0, 0)	1.20	1.62	1.30	2.87	4.14	3.06
		(10, 0, 0)	1.16	1.90	1.12	2.81	4.83	2.89
		(20, 0, 0)	1.17	1.94	1.19	2.60	4.36	2.81
	3/8 of AFOV	(1, 0, 39.75)	1.14	2.13	1.24	2.86	5.22	3.20
		(10, 0, 39.75)	1.21	2.48	1.29	3.19	7.11	3.06
		(20, 0, 39.75)	1.26	2.52	1.05	2.08	5.58	2.08
	Center	(0, 1, 0)	1.18	1.75	1.34	2.43	3.79	2.54
		(0, 10, 0)	1.22	1.92	1.33	2.54	4.20	2.54
		(0, 20, 0)	1.32	2.25	1.41	2.71	7.08	2.71
	3/8 of AFOV	(0, 1, 39.75)	1.29	2.24	1.16	2.58	5.71	2.59
		(0, 10, 39.75)	1.52	2.71	1.46	2.91	6.54	3.35
		(0, 20, 39.75)	1.65	3.36	1.88	3.76	8.18	3.96
Quadra 322 MRD	Center	(1, 0, 0)	2.55	2.62	2.85	5.68	6.45	7.03
		(10, 0, 0)	3.76	3.27	2.95	7.24	7.98	7.78
		(20, 0, 0)	5.24	3.97	3.62	10.39	9.39	8.03
	3/8 of AFOV	(1, 0, 39.75)	2.09	2.35	2.24	4.76	5.70	4.68
		(10, 0, 39.75)	2.78	3.14	2.89	5.85	7.64	5.03
		(20, 0, 39.75)	4.63	3.31	3.20	8.61	6.81	5.76
Quadra 85 MRD	Center	(1, 0, 0)	2.62	2.70	2.72	5.02	5.66	4.82
		(10, 0, 0)	2.86	2.72	2.78	6.66	6.43	5.86
		(20, 0, 0)	5.24	3.40	2.94	9.27	9.71	5.79
	3/8 of AFOV	(1, 0, 39.75)	2.22	2.44	2.40	4.80	5.71	4.84
		(10, 0, 39.75	3.31	3.02	2.71	6.35	6.67	5.95
		(20, 0, 39.75)	4.29	2.66	2.23	8.55	10.78	5.82



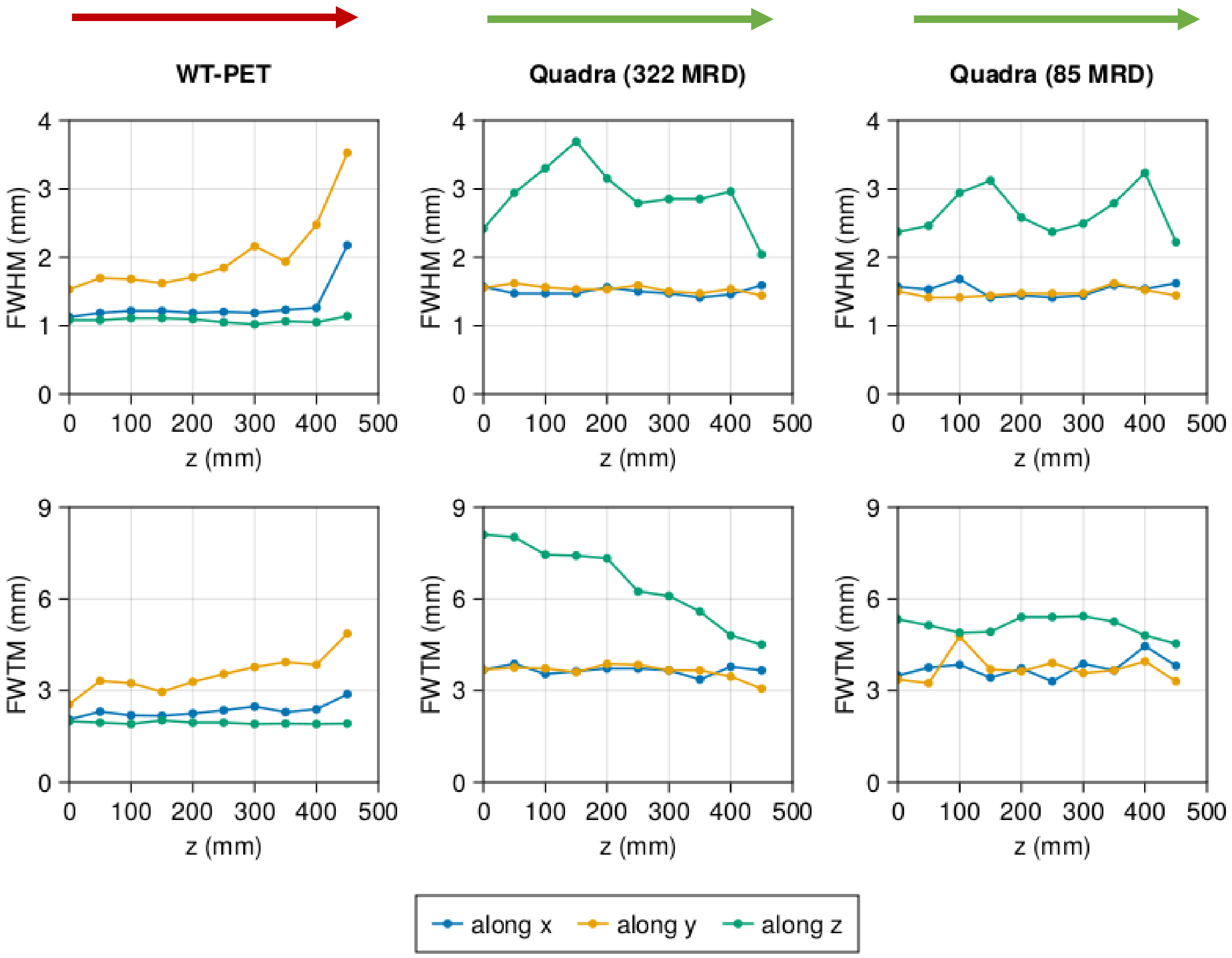
NEMA system characterization

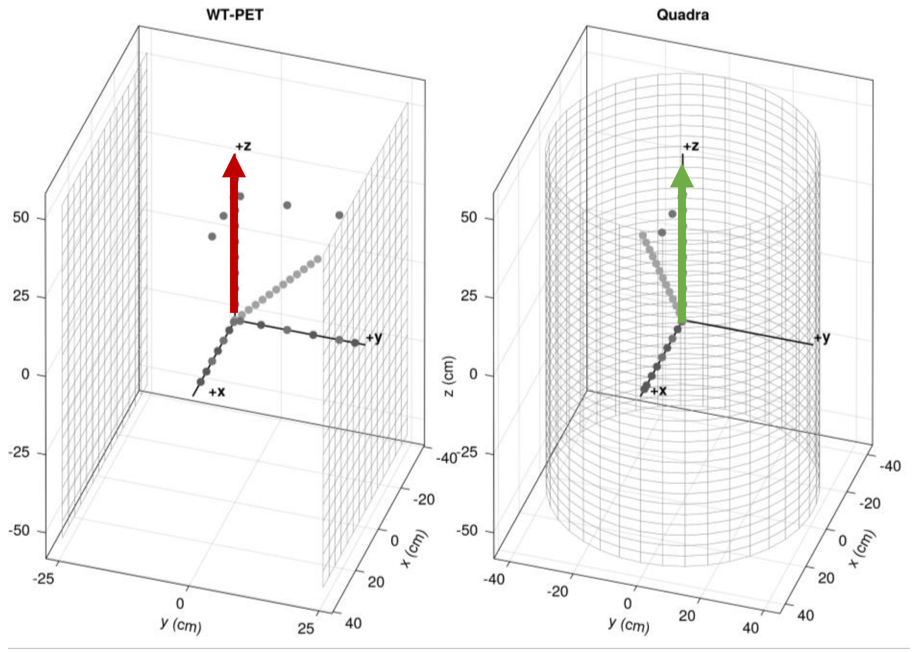
Spatial resolution: additional point sources



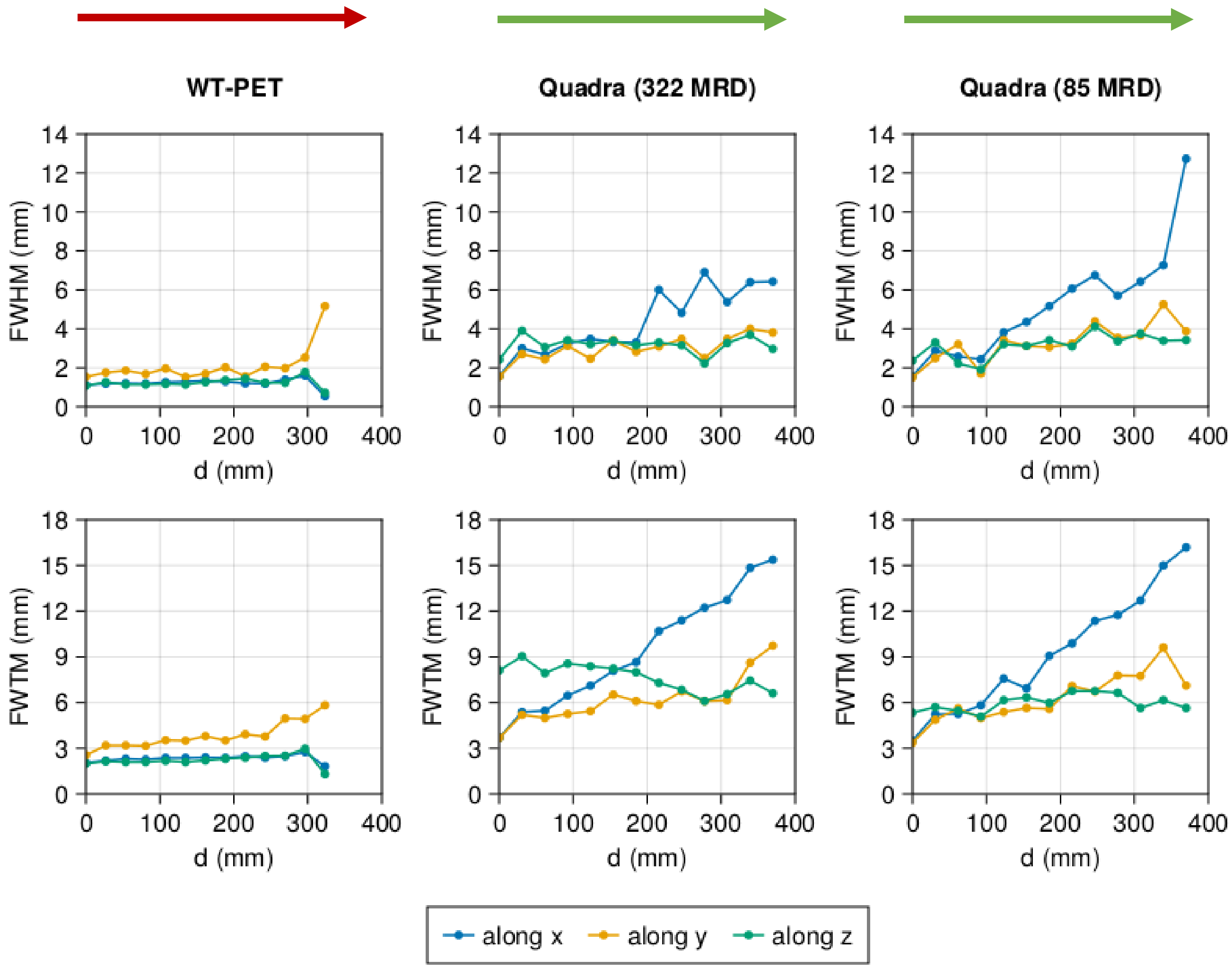


Spatial resolution: additional point sources





Spatial resolution: additional point sources



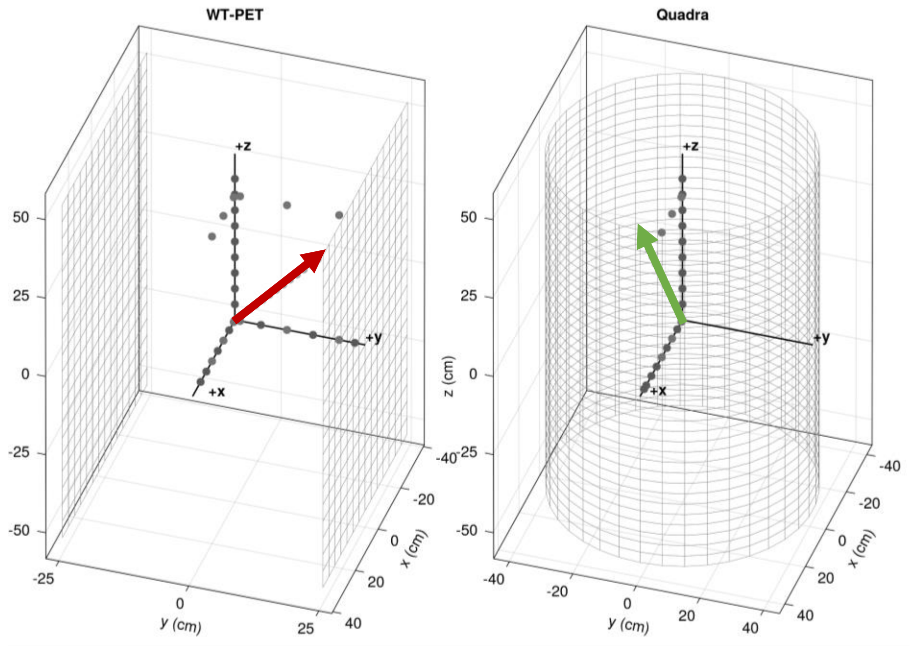
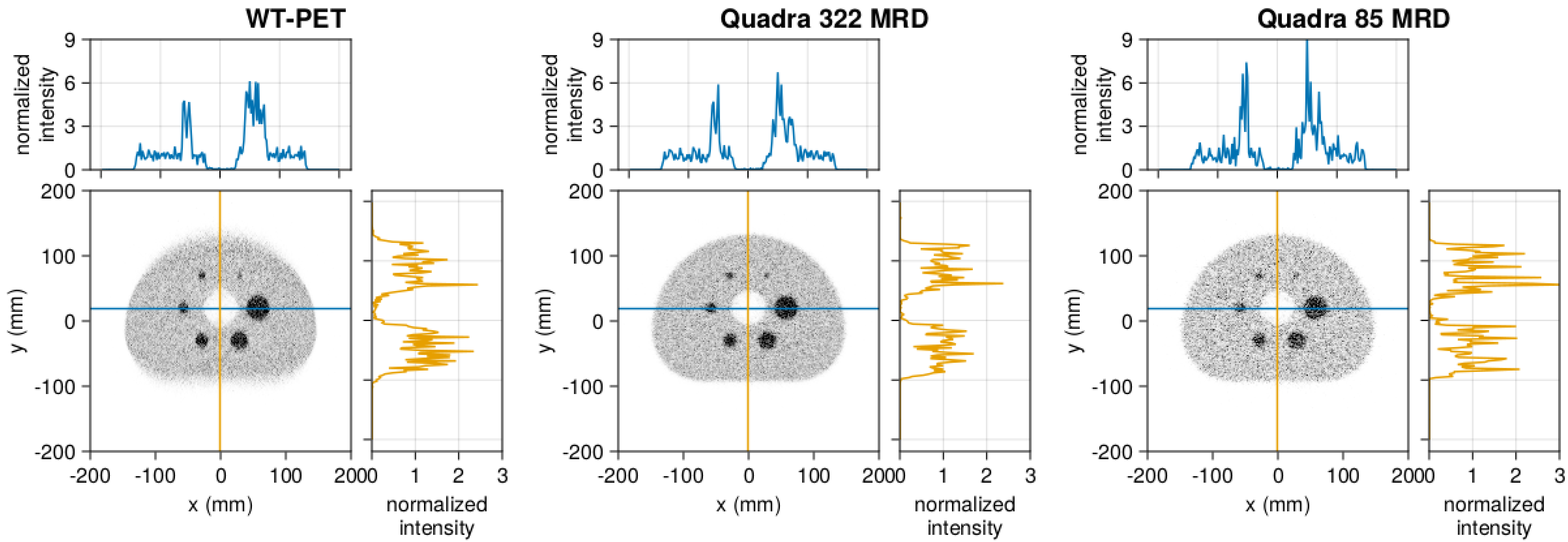


Image quality: visual



- **4:1 activity ratio**
- **30 s acquisition**
- **trues only**

Image quality: contrast recovery

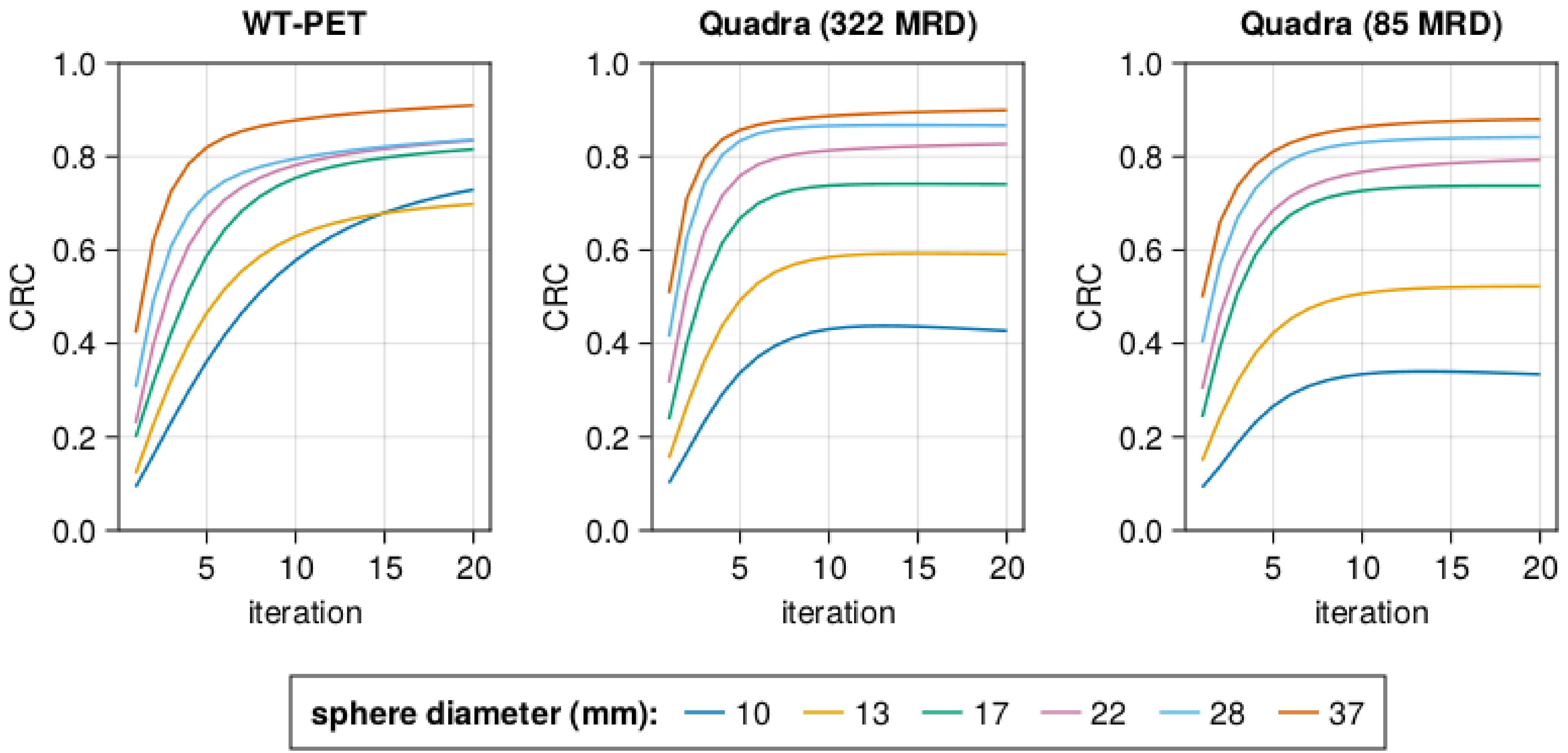


Image quality: additional lesions

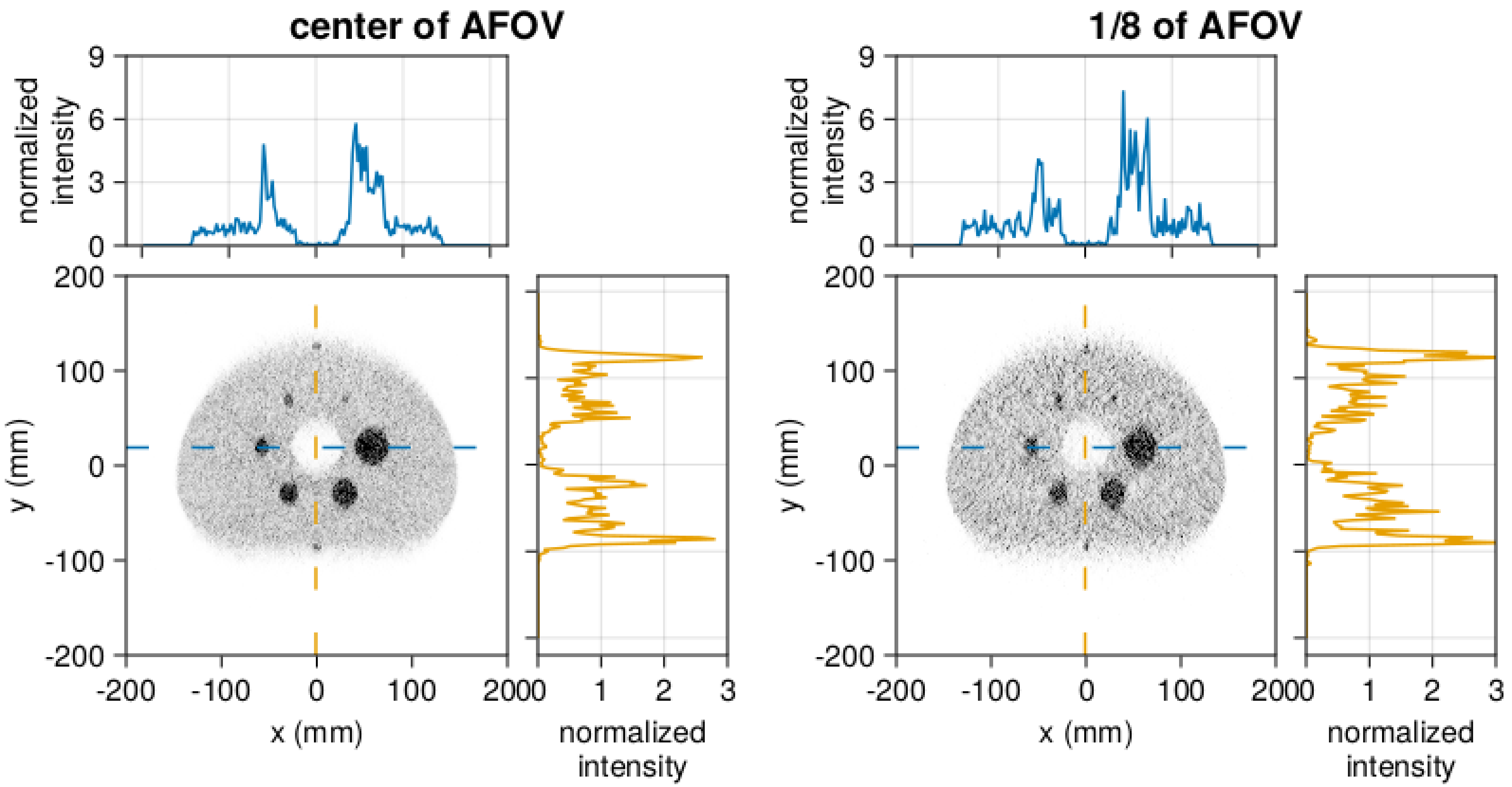


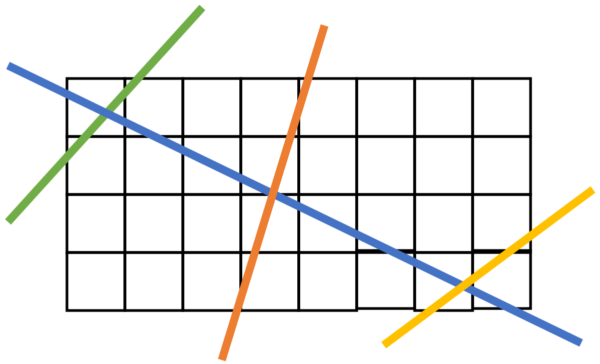
Image reconstruction

PETRecon

- Iterative listmode reconstruction on the GPU
- Written in Julia
  - High level but fast (similar speed to C++)
  - Good support for GPU programming with CUDA
  - Good support for deep learning
  - Supports auto differentiation
- Implementations for:
  - Emission tomography (MLEM)
  - Transmission tomography (MLTR)
  - Simultaneous estimation of activity and attenuation (MLAA)

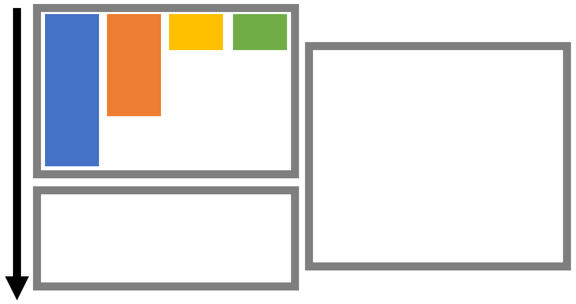
PETRecon

Siddon's algorithm



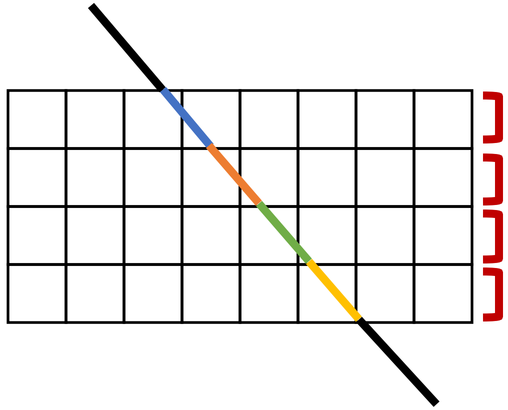
CPU

GPU

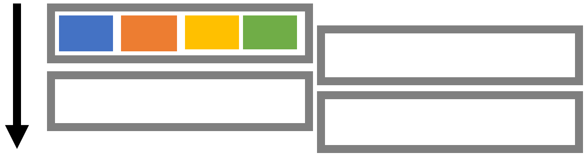


- Thread 1
- Thread 2
- Thread 3
- Thread 4

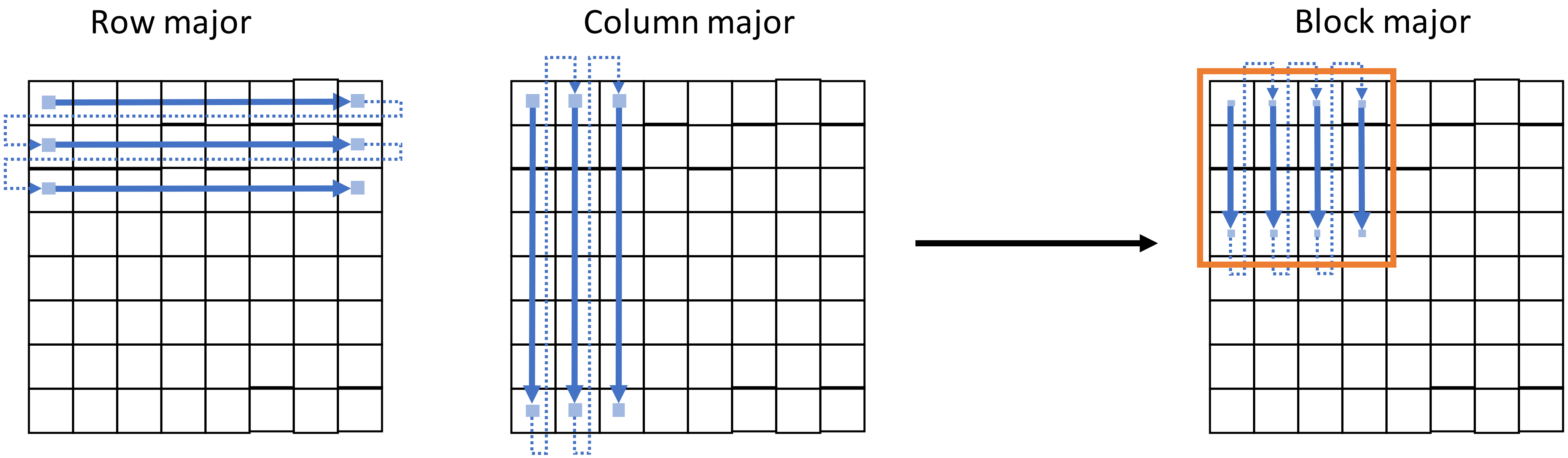
Slice-based raytracing

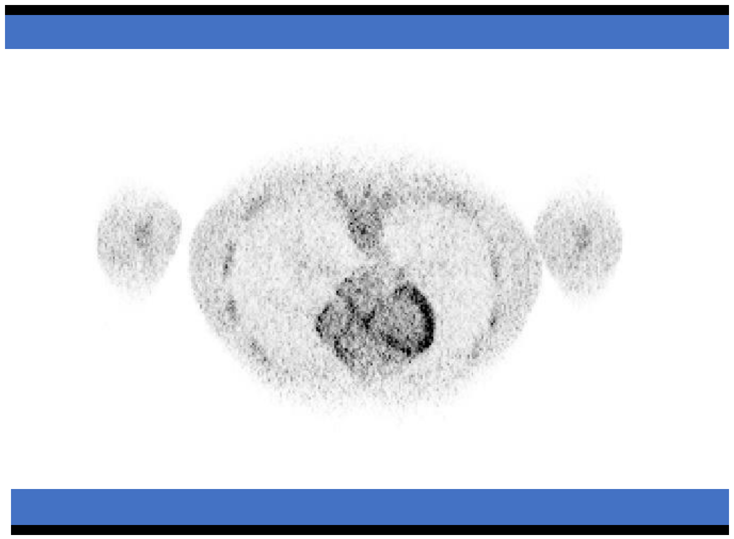


GPU



PETRecon

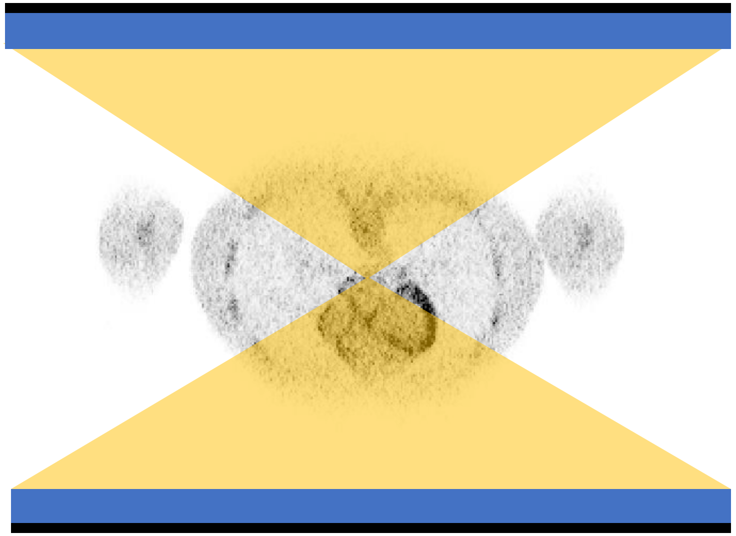




- **Male XCAT phantom (BMI=22.7)**
- **30 s acquisition**
- **trues only**

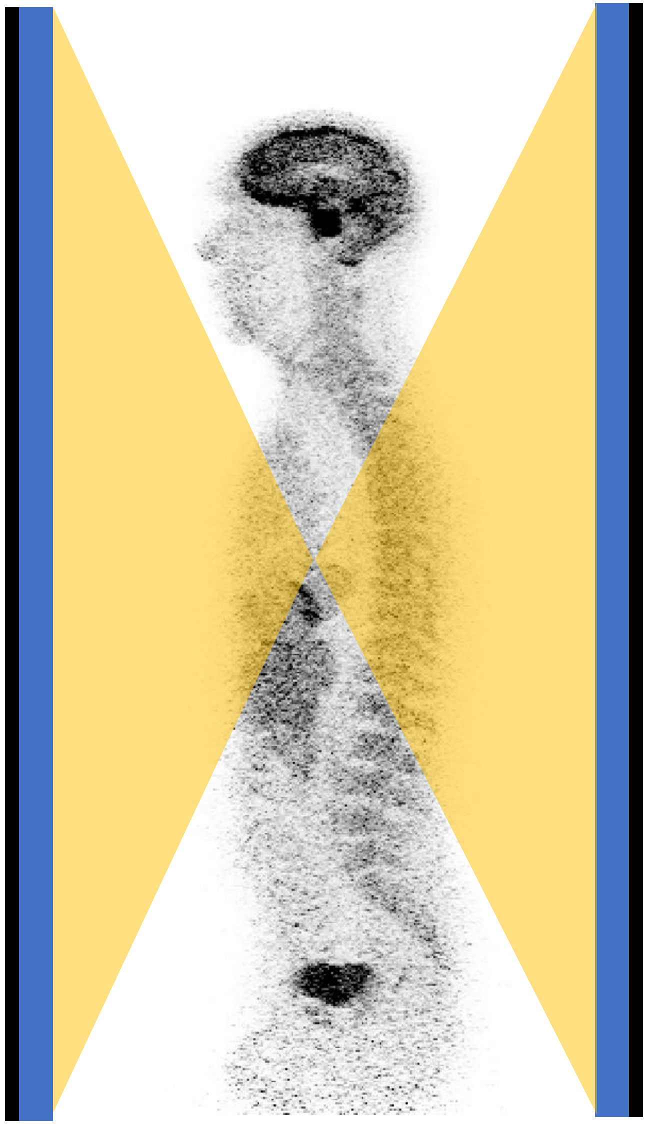
Limited angle artefacts

Angular coverage

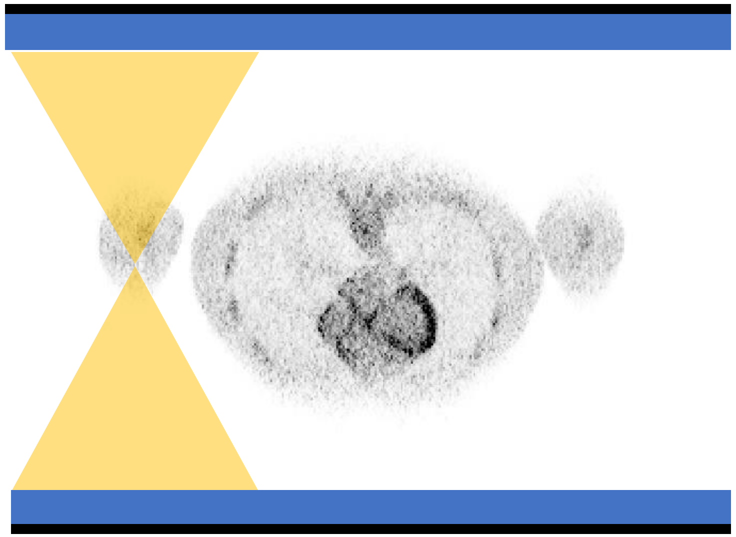


224°/360° = **62%**

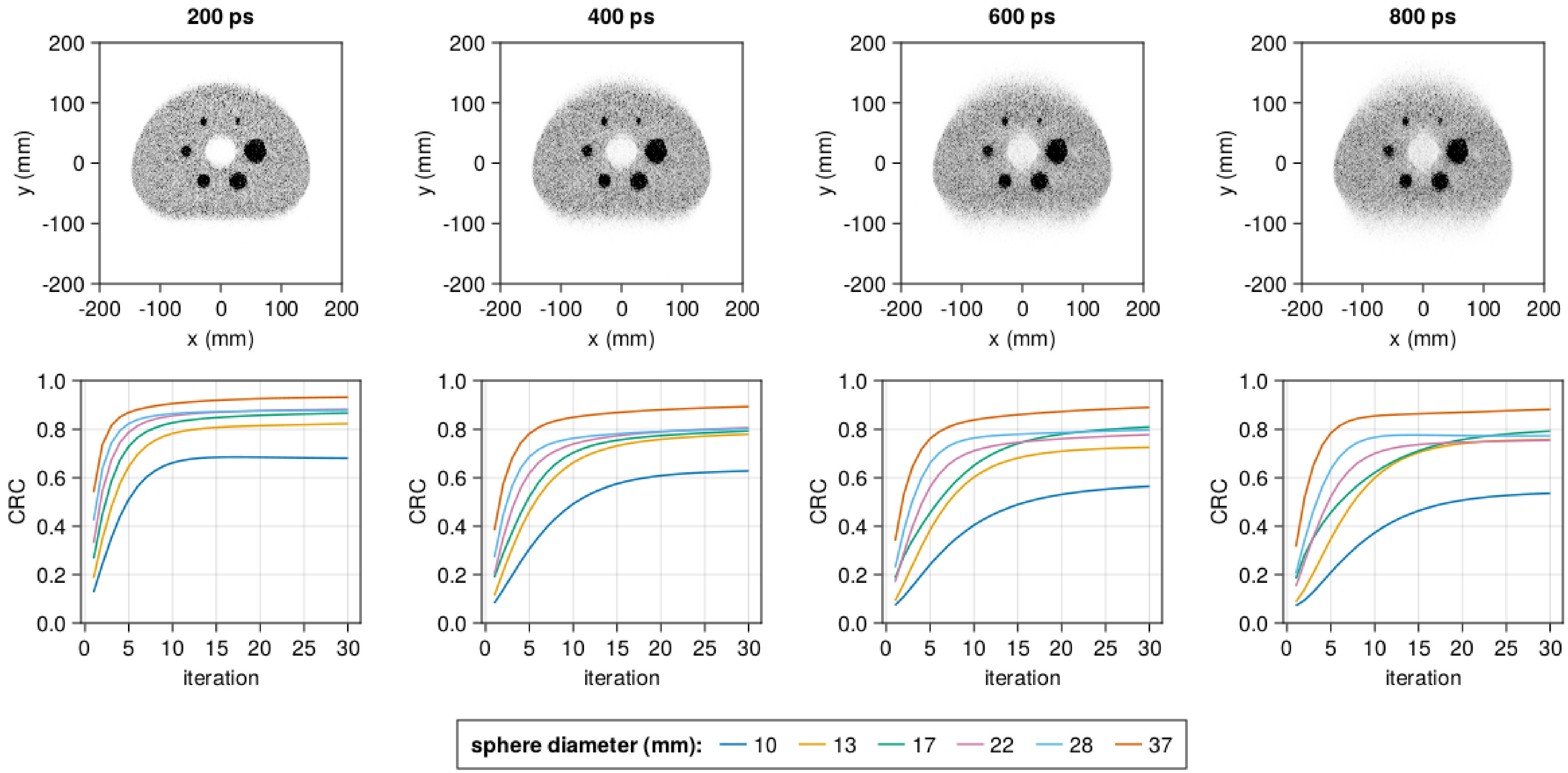
259°/360° = **72%**



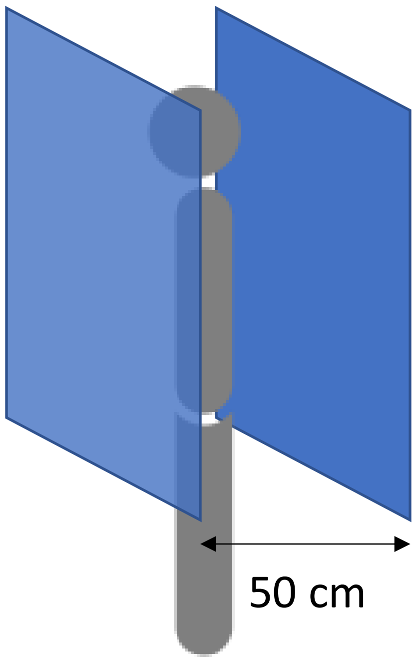
Angular coverage

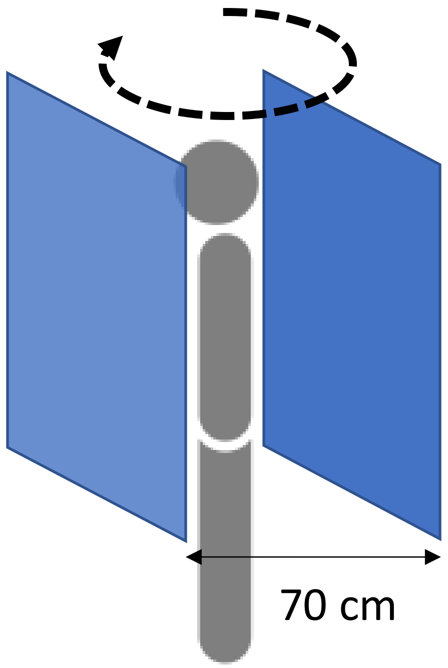


Impact of TOF

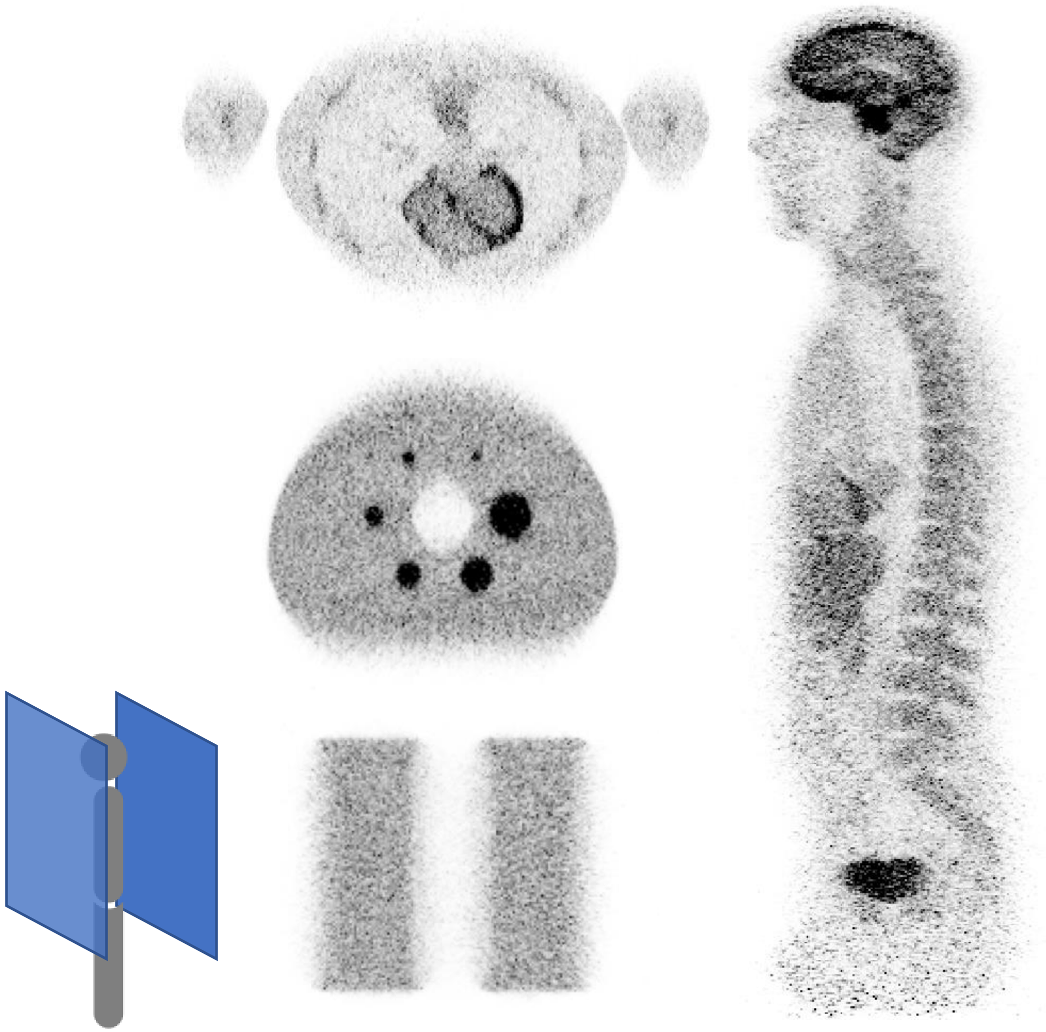


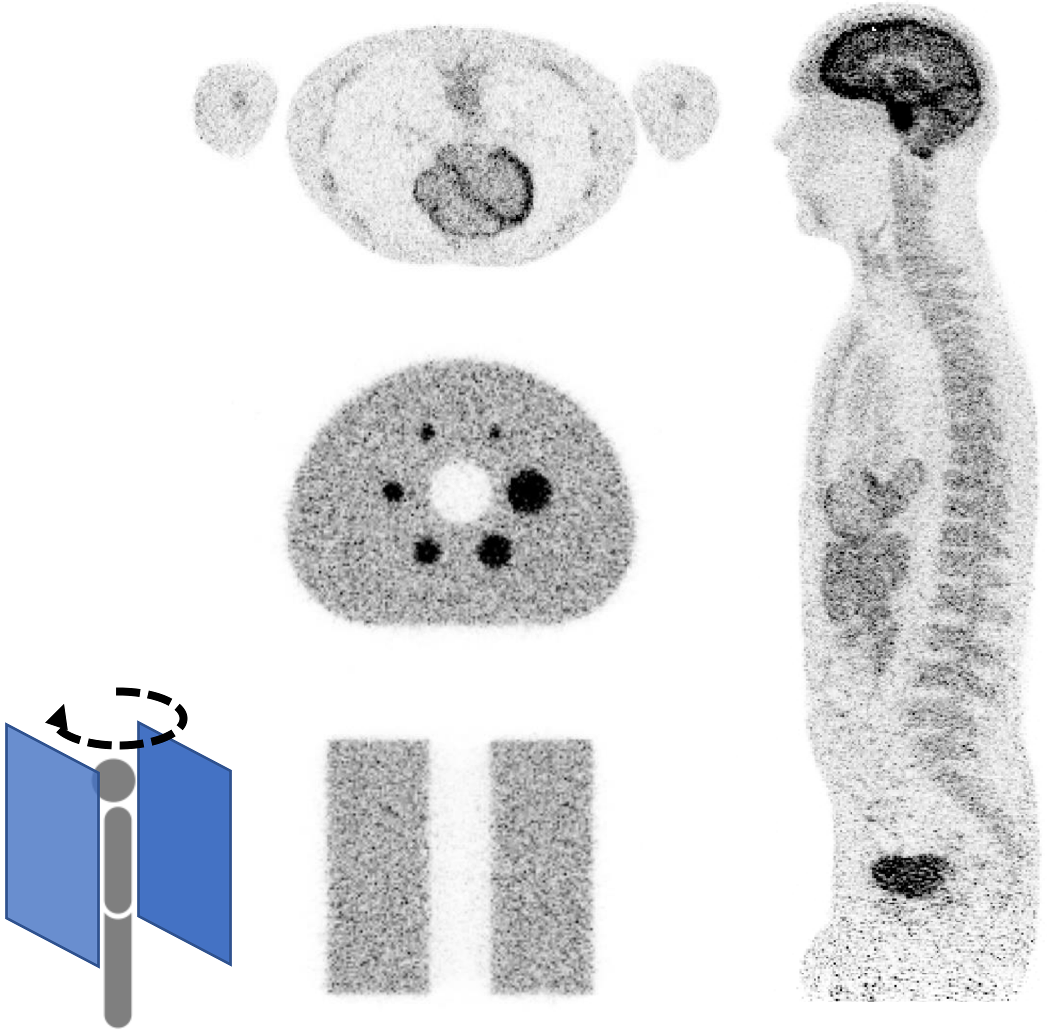
Rotating configuration



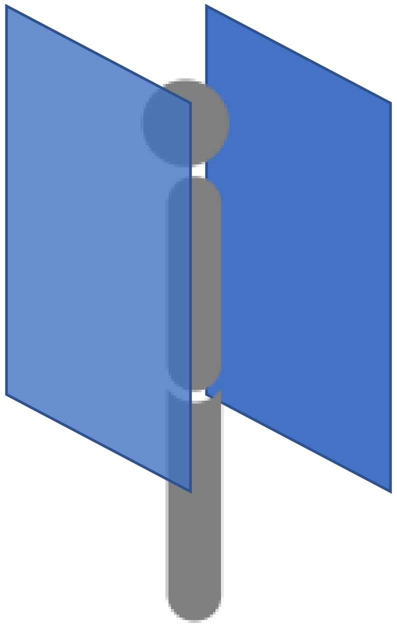


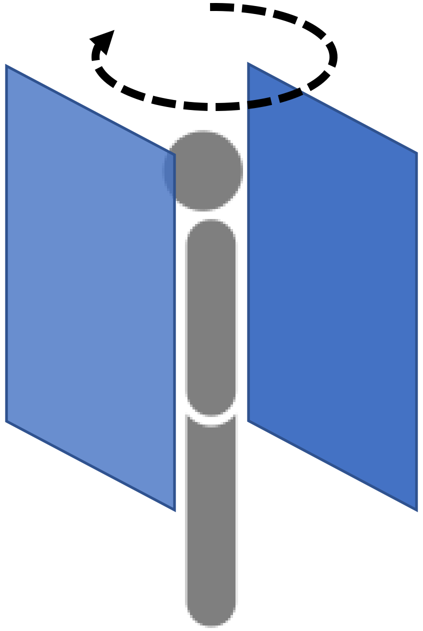
Rotating configuration





Rotating configuration





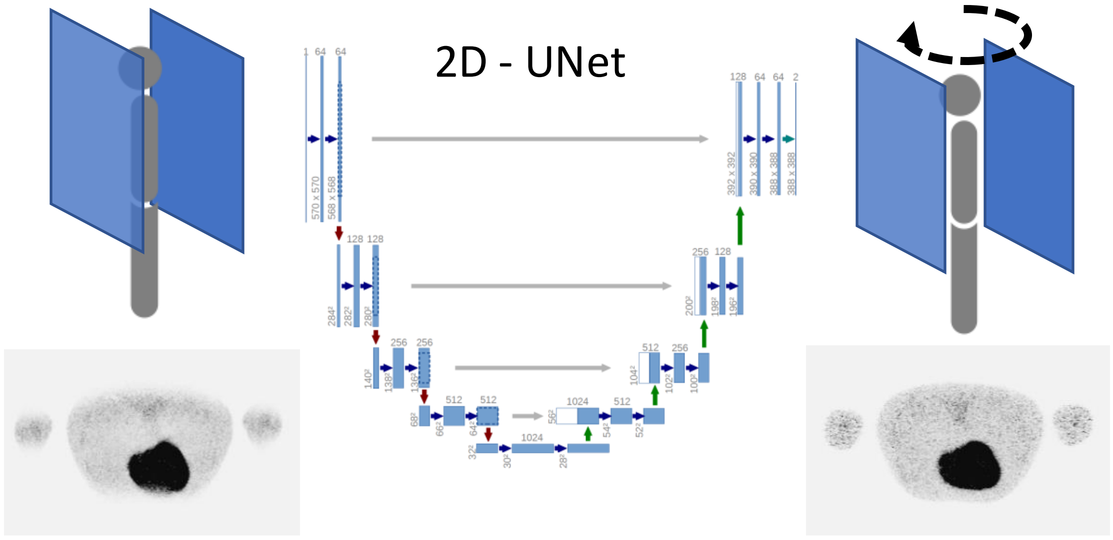
- Remove limited angle artefacts

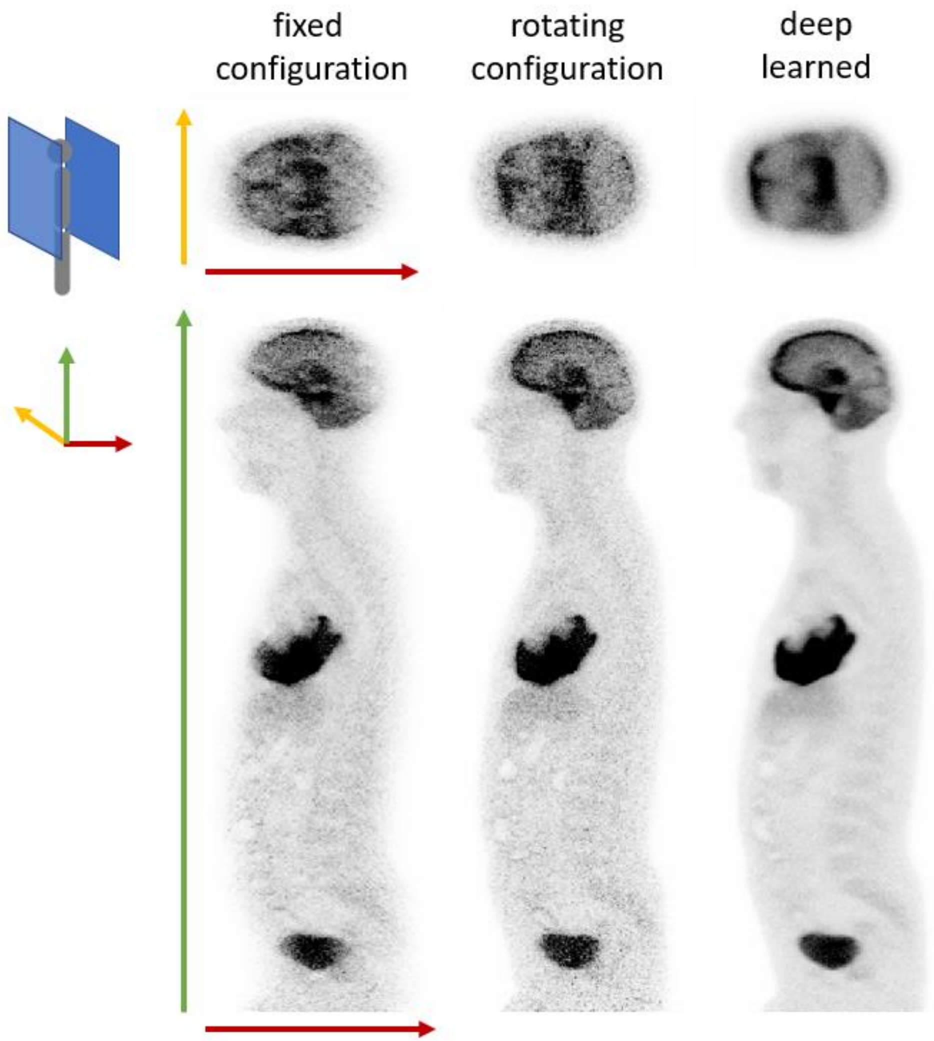
- Reduced sensitivity (about 33% lower)
- Increased system complexity
- Decreased patient throughput

→ Other solution may be preferable (e.g. AI based)

Deep learning artefact correction

Artefact correction as a **post-processing** step





Deep learning artefact correction

Artefact correction as a **regularization** step

$$\hat{x} = argmin_x[f(Hx + e, y) + \lambda R(x)]$$

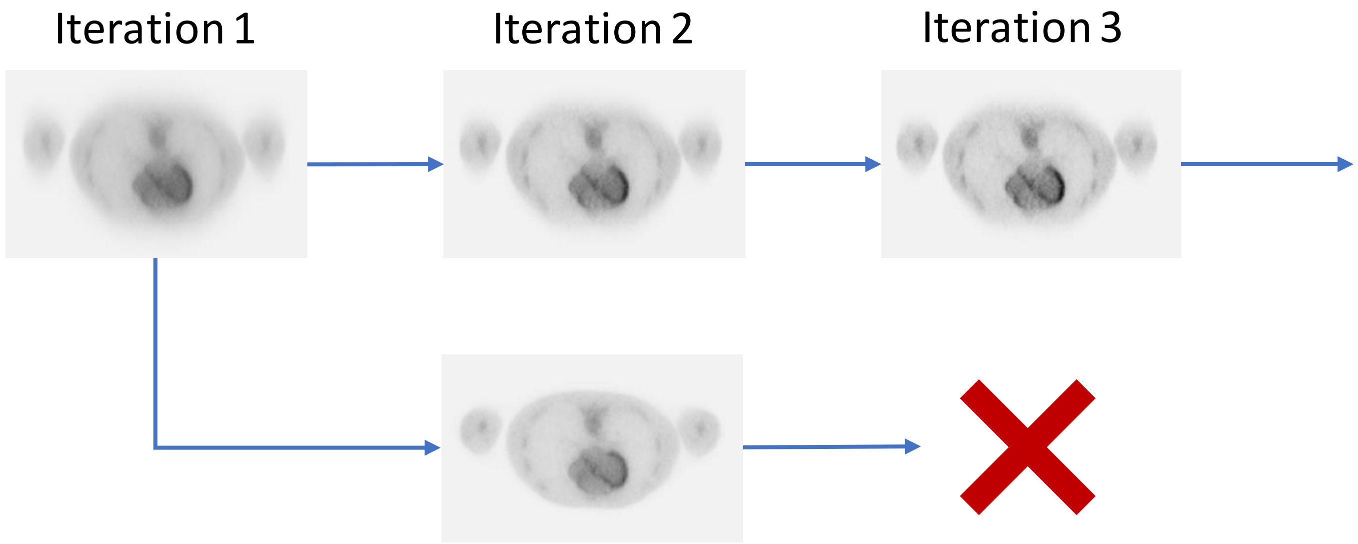
data consistency

regularization

$$R(x) = \|x - F(x)\|_2$$

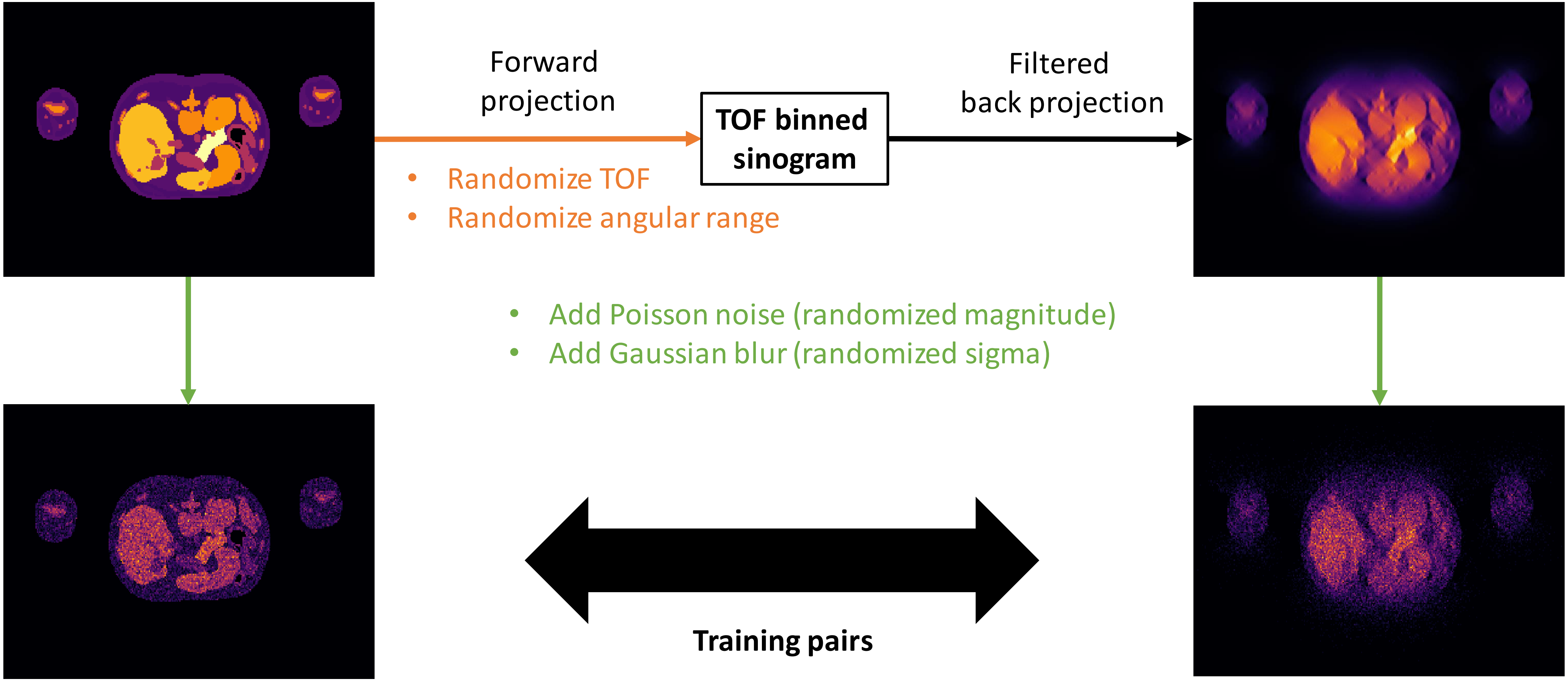
Artefact correcting neural network

Deep learning artefact correction



Network needs to be trained on a wide variety of inputs!

Deep learning artefact correction

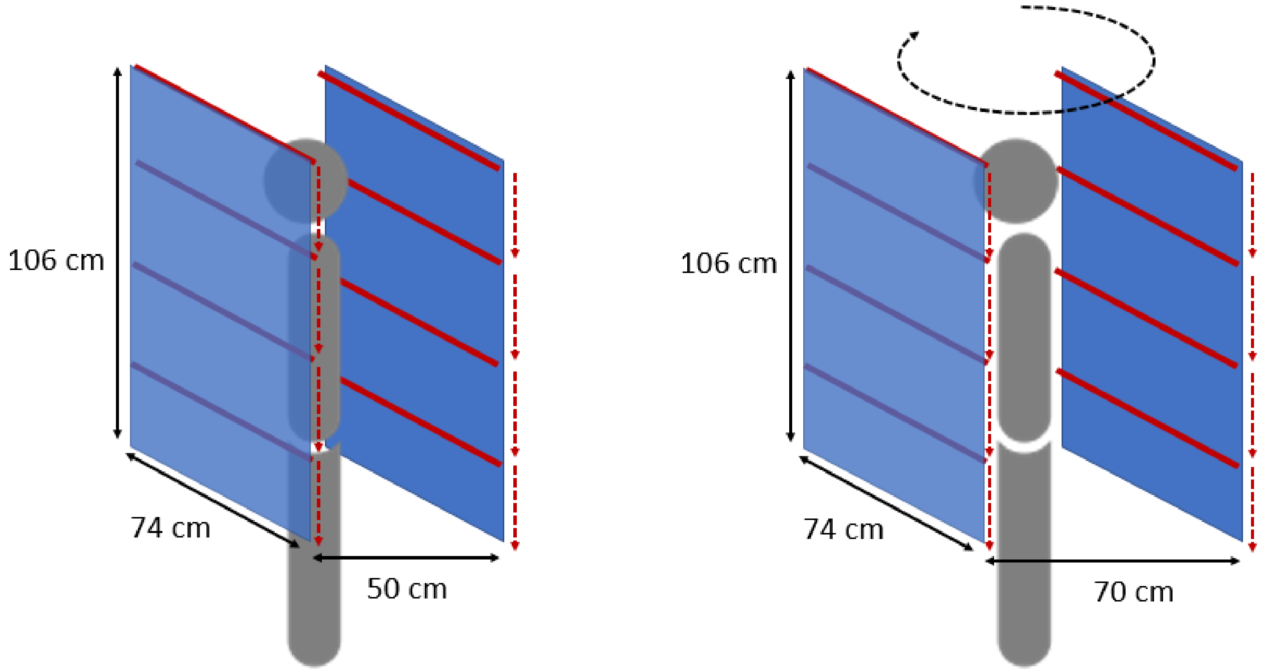


CT-less attenuation correction

Available methods

- **Transmission based – MLTR** ←
- **Emission based – MLAA** ←
- Deep learned (Florence)

Transmission based



fixed configuration

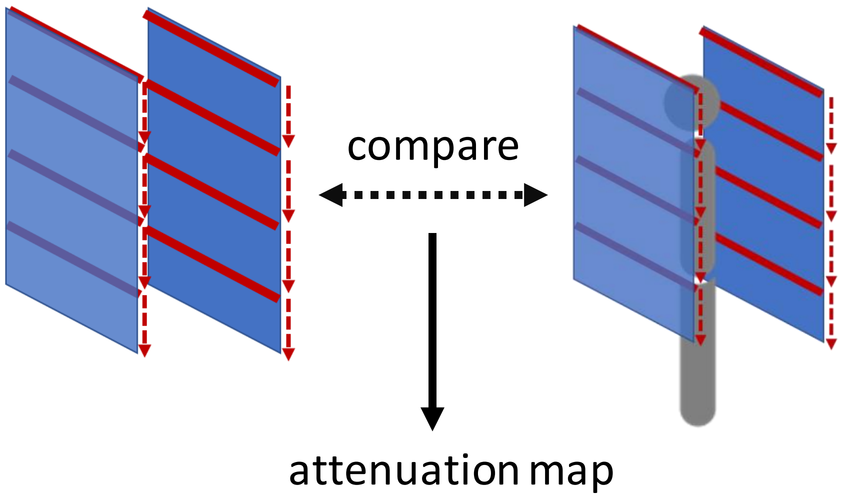
rotating configuration

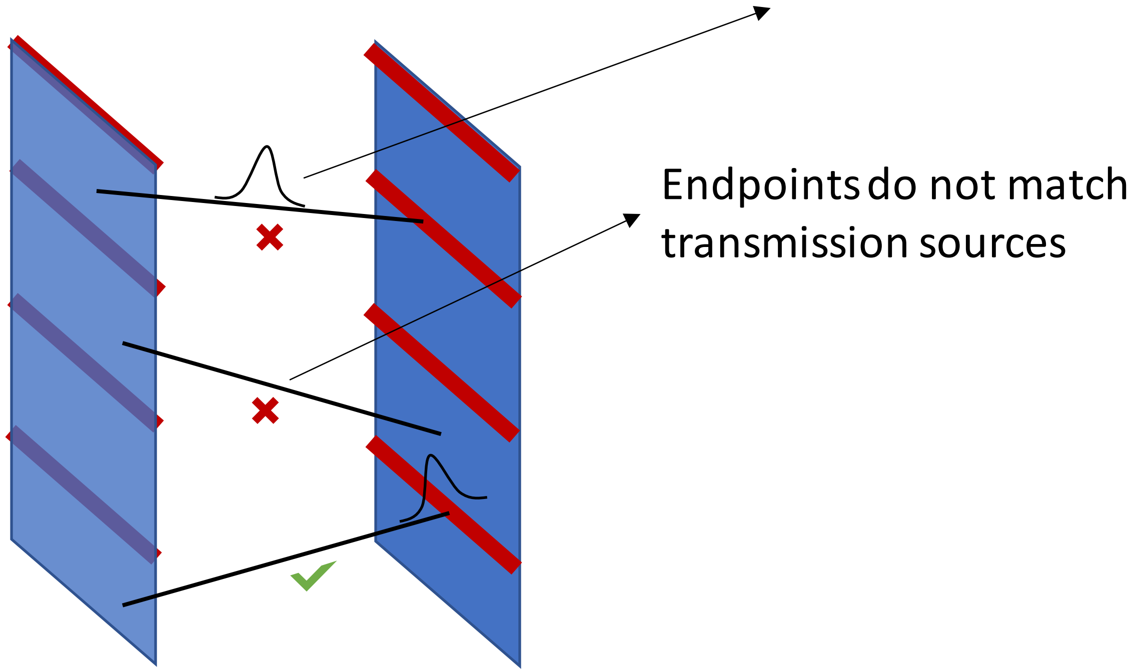
8x 3MBq Ge-68 transmission sources

3MBq → 10% of maximum detector count rate

CT-less attenuation correction

Transmission based

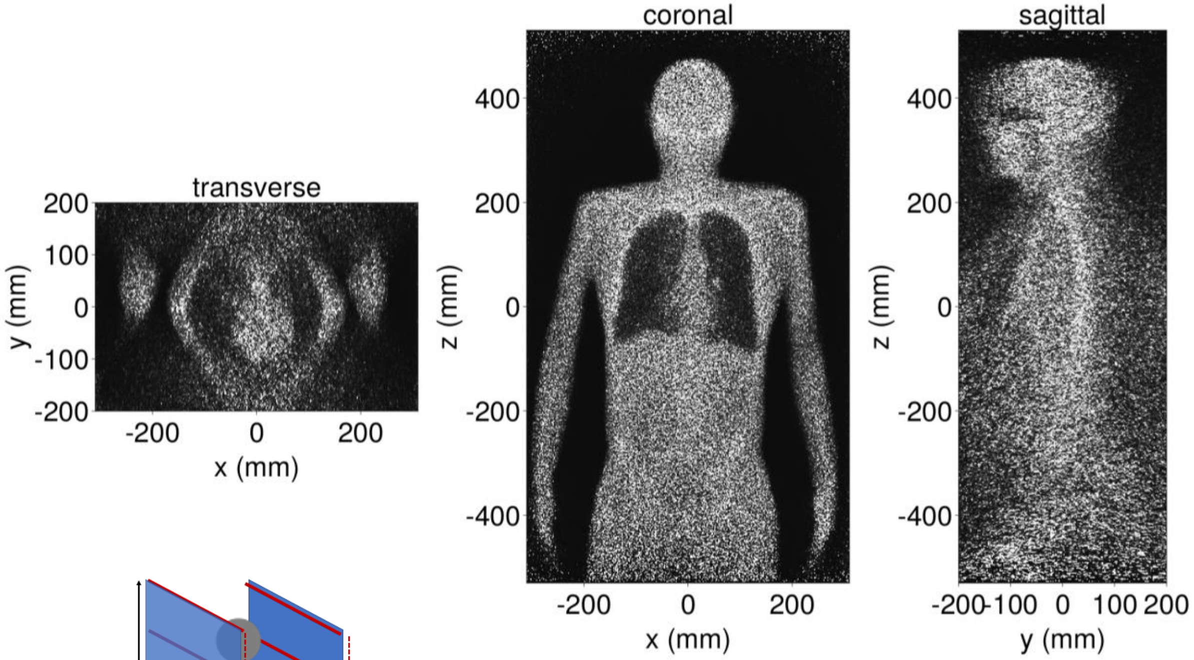




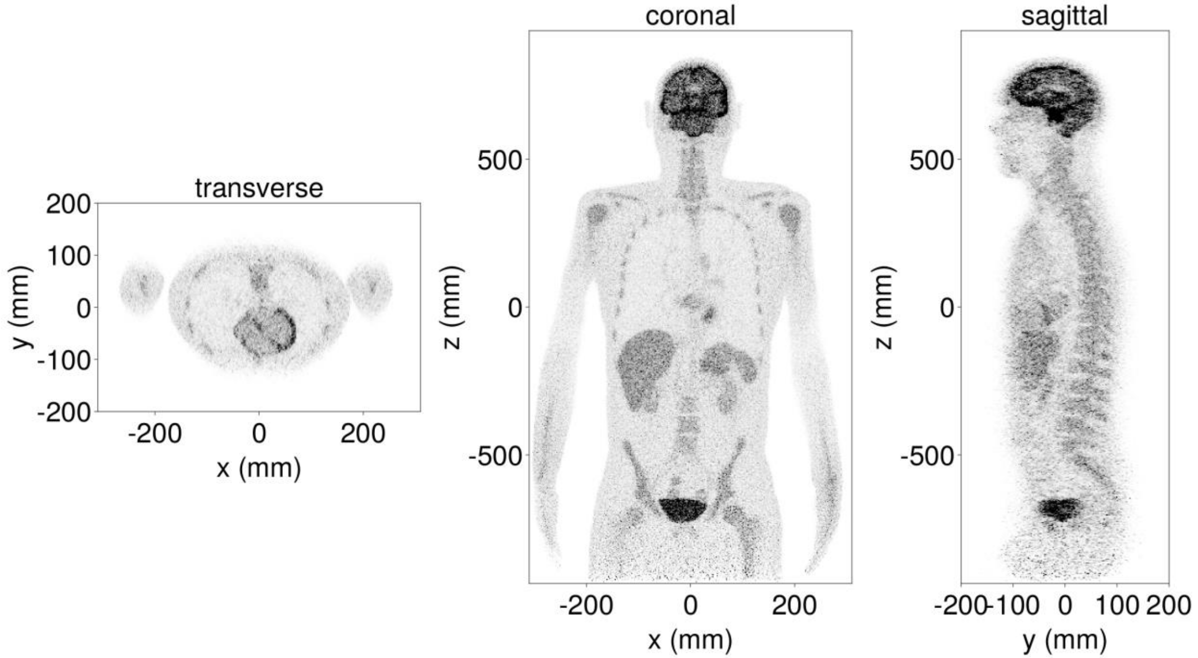
Can be done simultaneously with emission scan

But for the purpose of simulation done separately

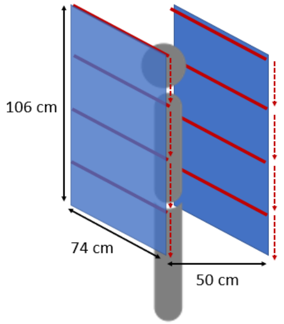
Transmission based: stationary WT-PET



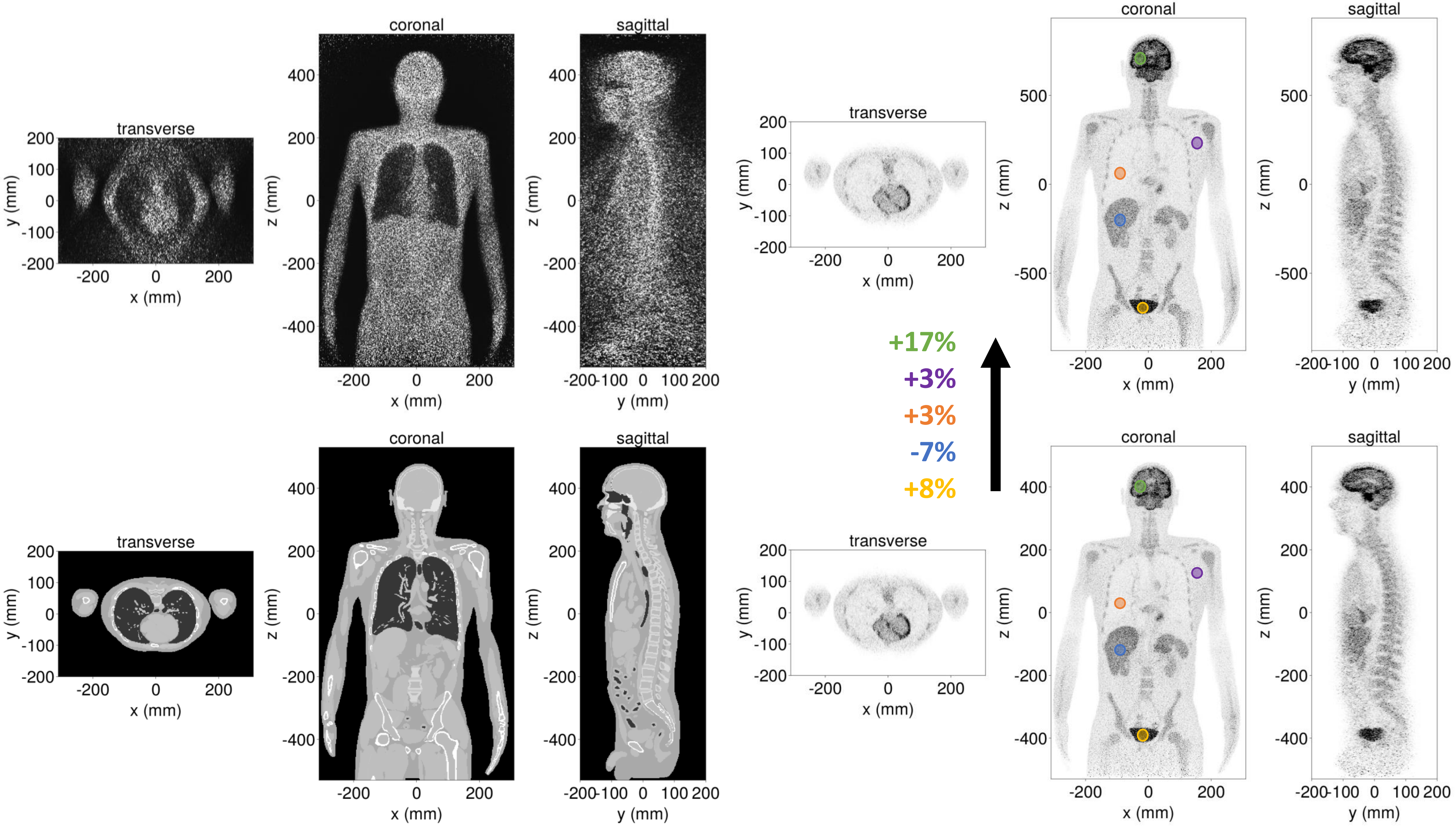
MLTR

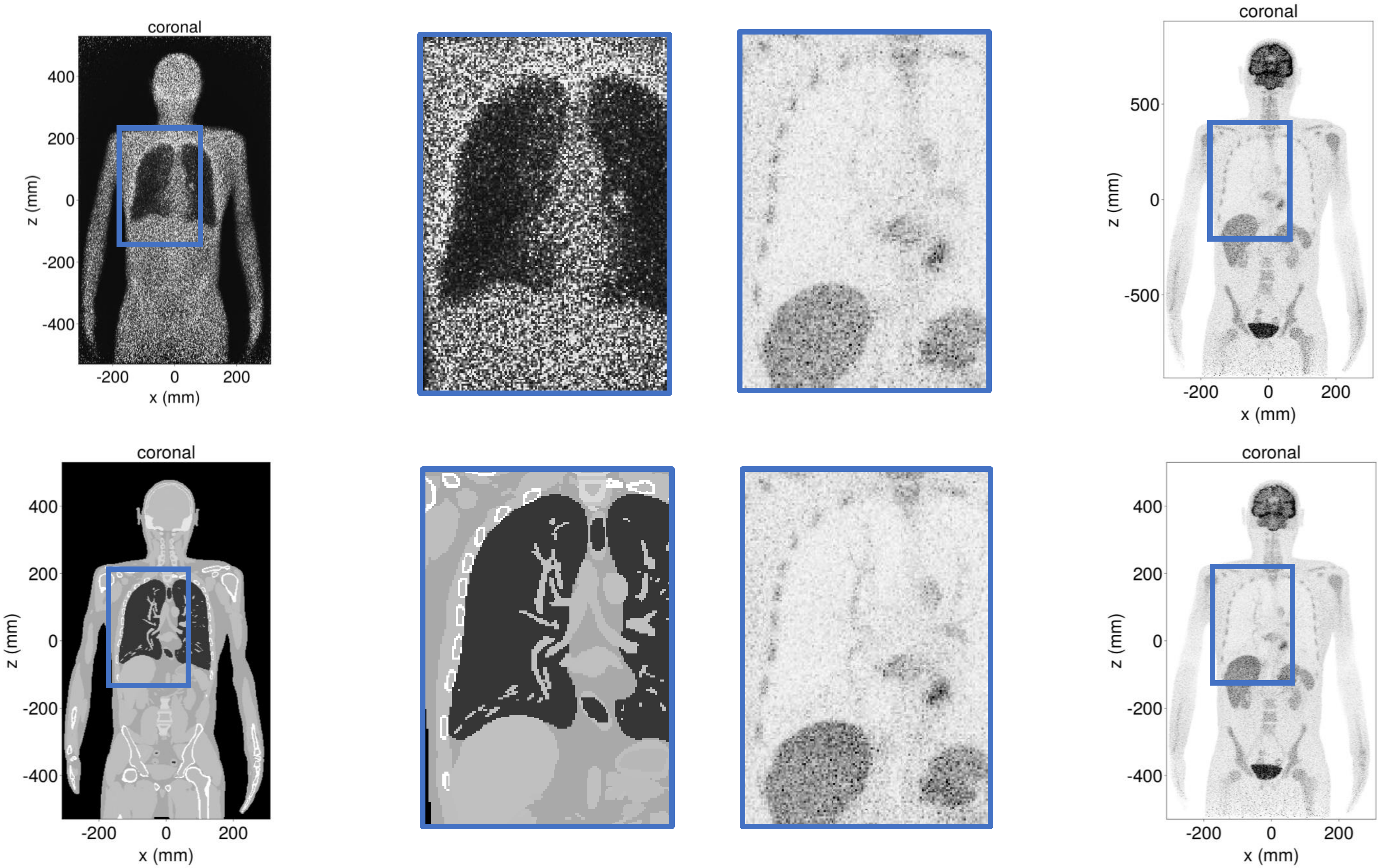


MLEM

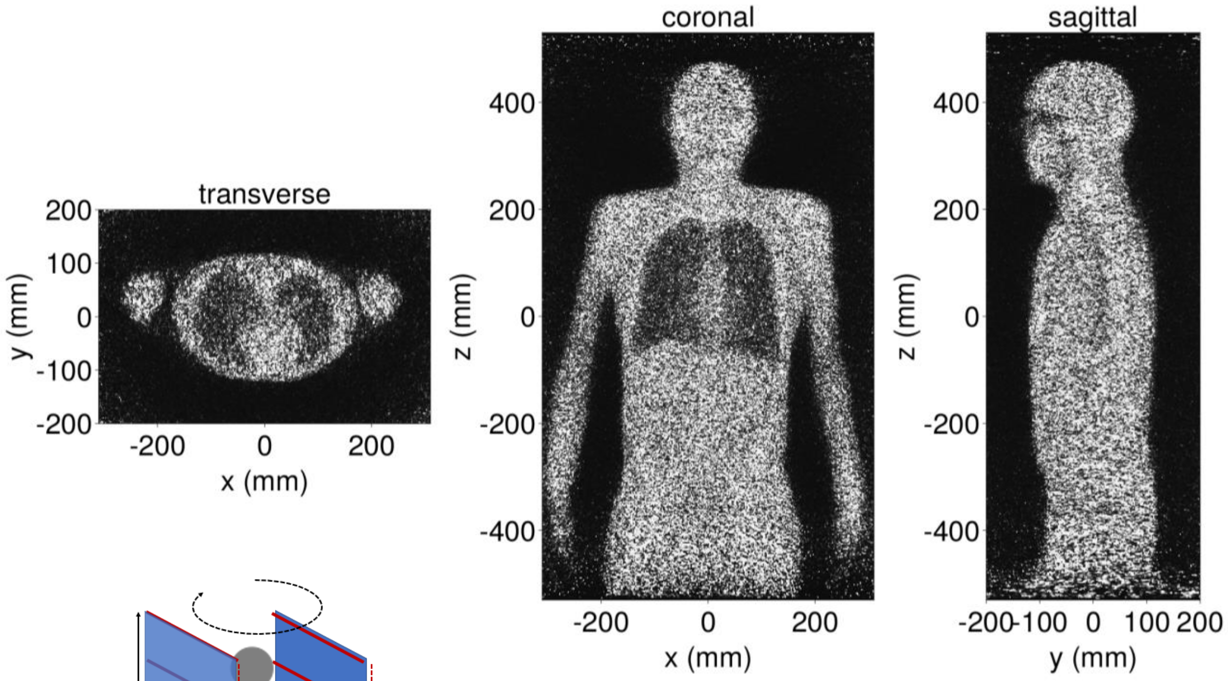


fixed configuration

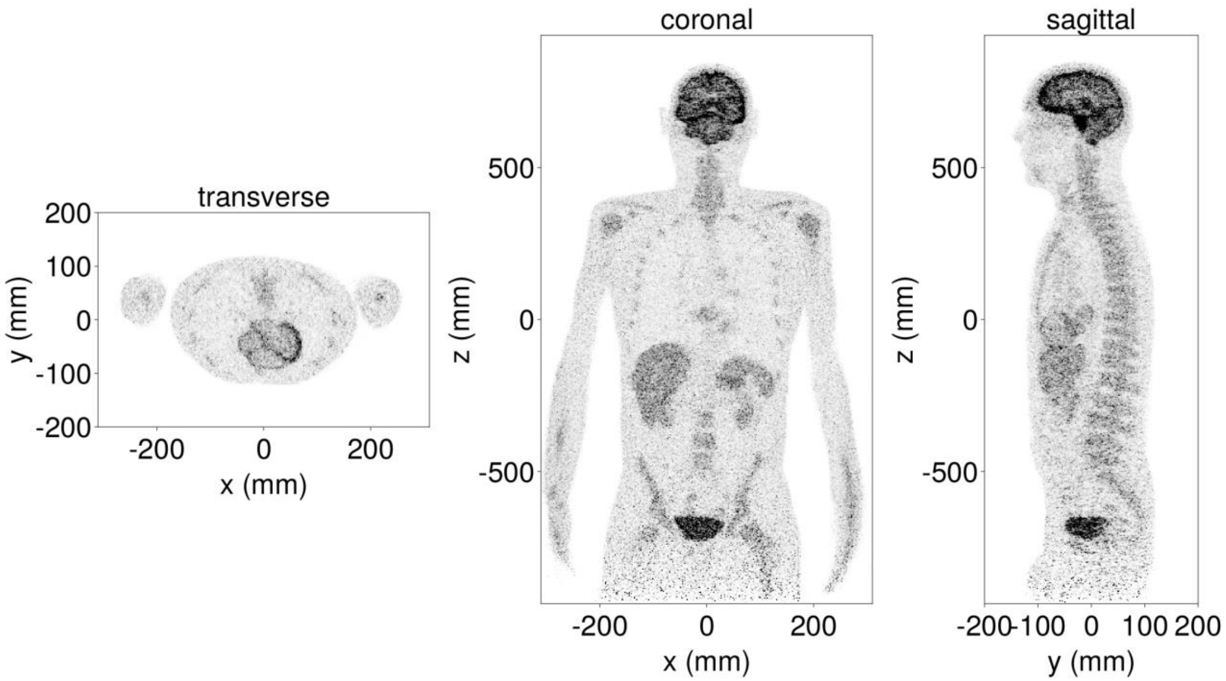

transverse
coronal
sagittal
x (mm)
y (mm)
z (mm)
+17%
+3%
+3%
-7%
+8%


coronal
400
200
0
-200
-400
z (mm)
-200
0
200
x (mm)
coronal
500
0
-500
z (mm)
-200
0
200
x (mm)
coronal
400
200
0
-200
-400
z (mm)
-200
0
200
x (mm)
coronal
400
200
0
-200
-400
z (mm)
-200
0
200
x (mm)

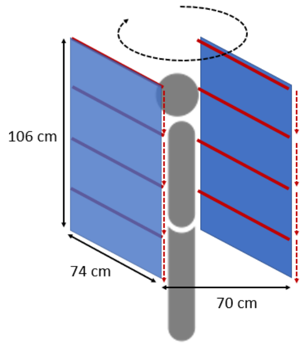
Transmission based: rotating WT-PET



MLTR

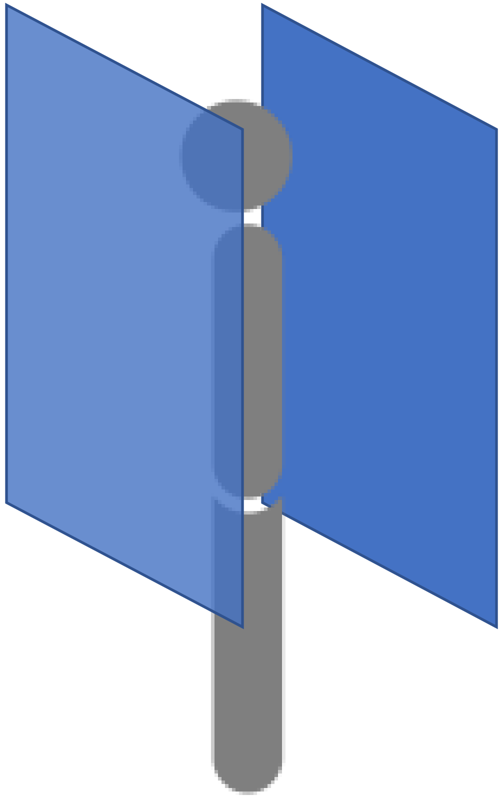


MLEM

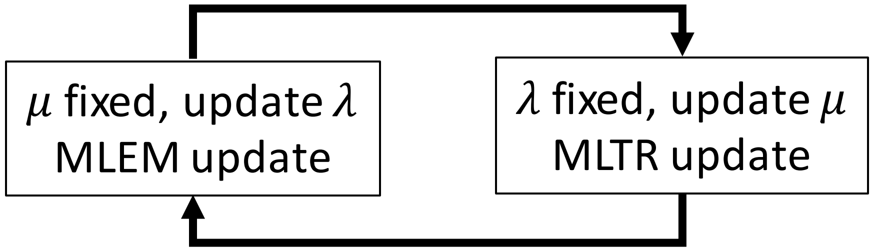


rotating configuration

Emission based

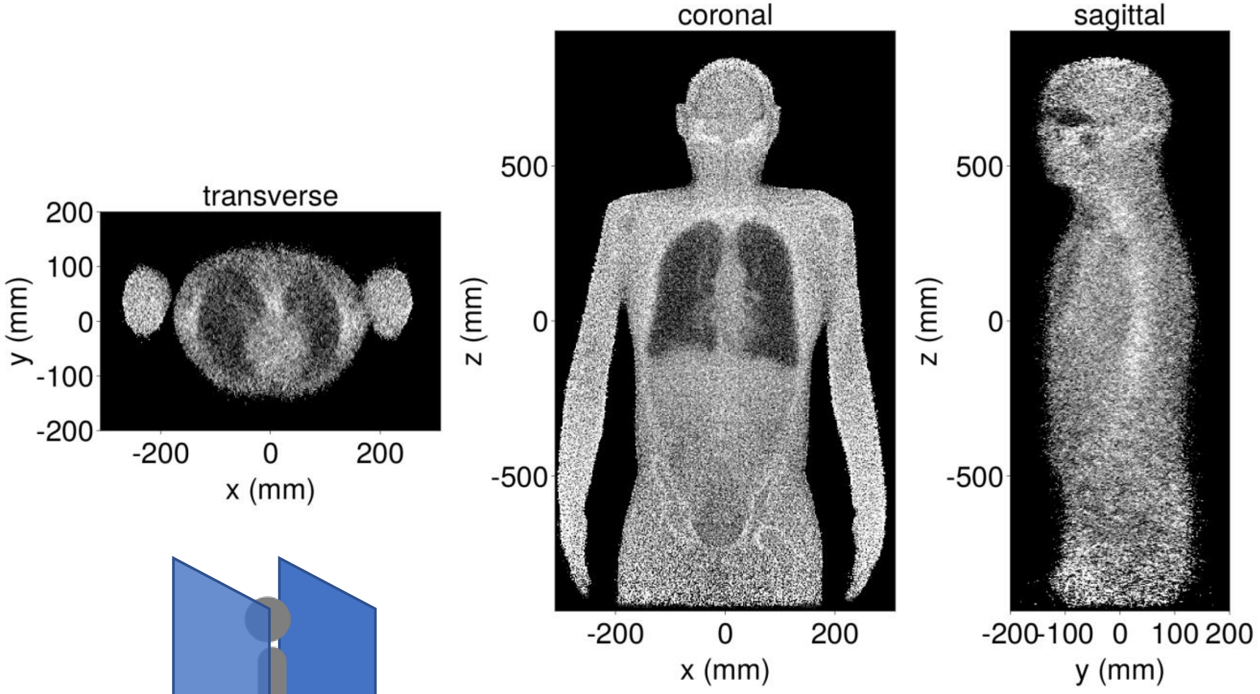


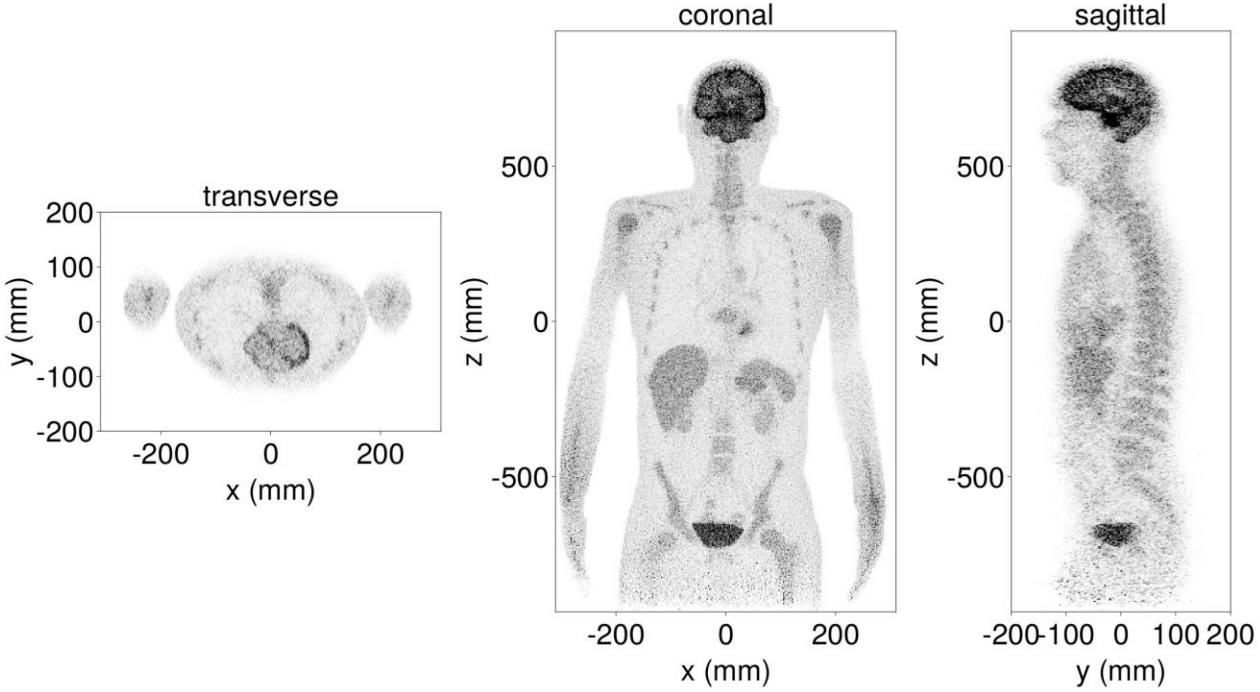
Maximum likelihood activity and attenuation (MLAA):

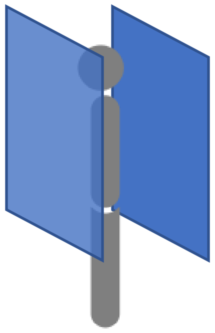


For TOF PET: attenuation / activity determined up to a constant
→ Additional constraint required (e.g. injected activity)

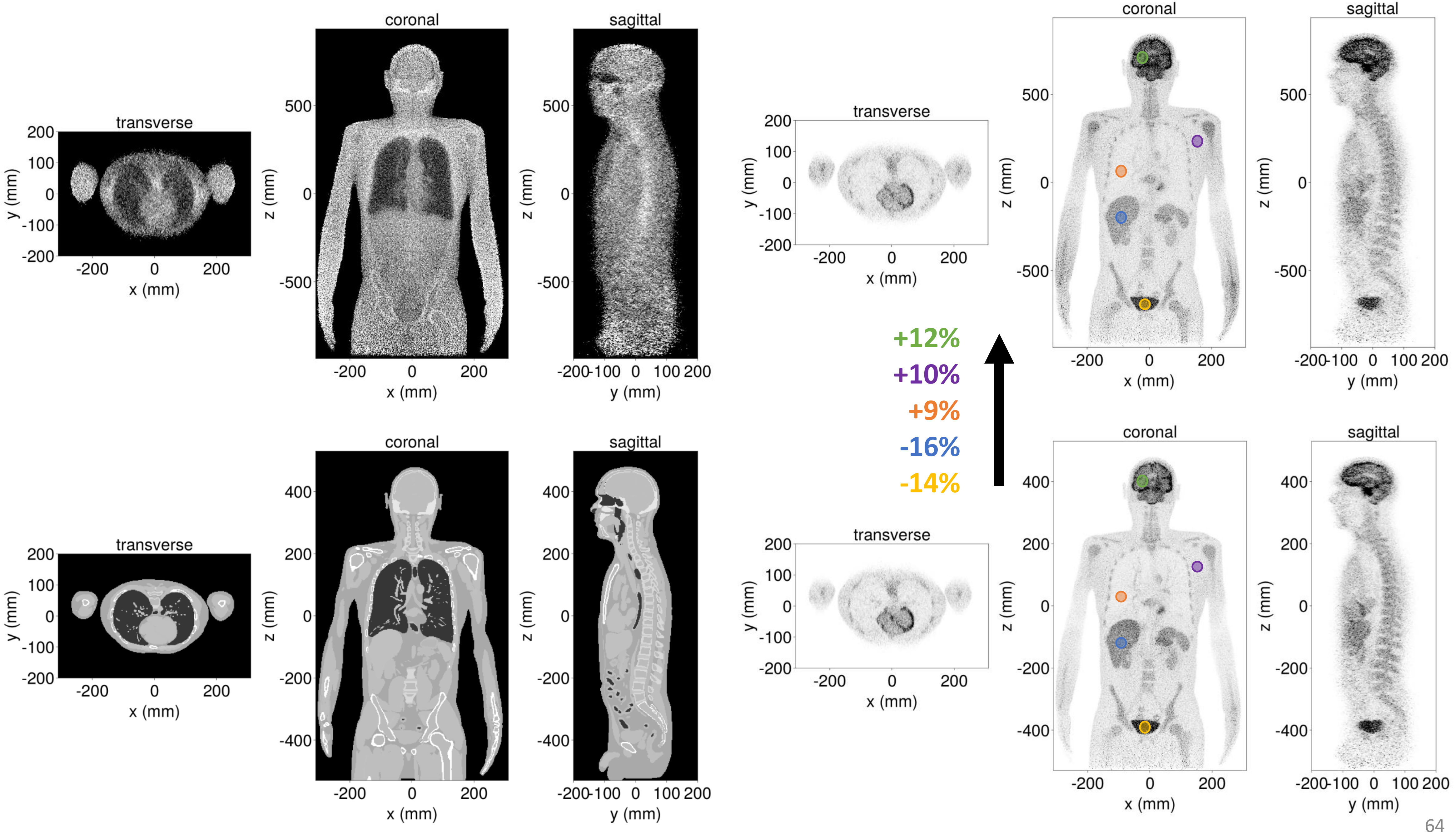
Emission based: stationary WT-PET



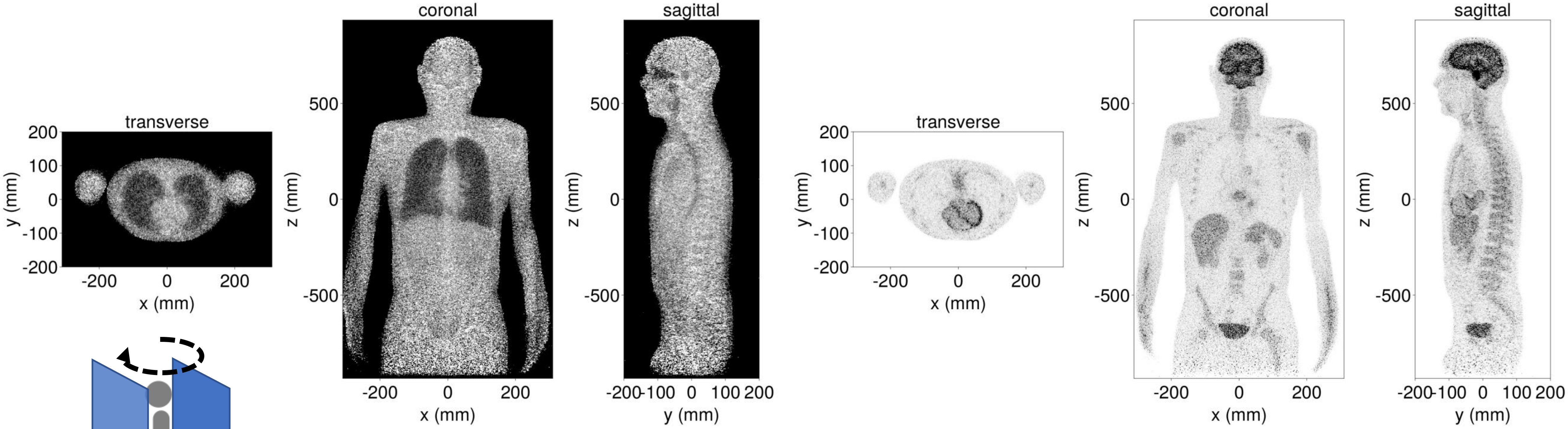


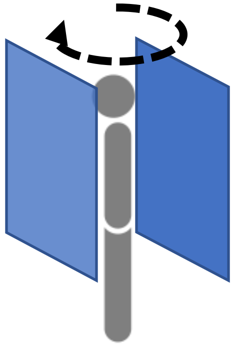


fixed configuration


transverse
coronal
sagittal
x (mm)
y (mm)
z (mm)
+12%
+10%
+9%
-16%
-14%

Emission based: rotating WT-PET





rotating configuration

Comparison

- MLTR
  - Better accuracy of activity map
  - Faster reconstruction
- MLAA
  - Reduced system complexity
  - Better reconstruction of attenuation map (for fixed configuration)

Comparison

MLTR

$$\mu_j^{(k+1)} = \mu_j^{(k)} \frac{\sum_{i \in B} l_{ij} \exp\left(-\sum_{j' \in J} l_{ij'} \mu_{j'}^{(k)}\right)}{\sum_{i \in T} l_{ij}}$$

MLEM

$$\lambda_j^{(k+1)} = \frac{\lambda_j^{(k)}}{\sum_{i \in I} H_{ij}} \sum_{i \in E} \frac{H_{ijt}}{\sum_{j' \in J} H_{ij't} \lambda_{j'} + r_i + s_i}$$

- B = blank scan
- T = transmission scan
- E = emission scan
- I = space of possible LORs

MLAA

$$a_i^{(k)} = \exp\left(-\sum_{j \in J} l_{ij} \mu_j^{(k)}\right)$$

$$\lambda_j^{(k+1)} = \frac{\lambda_j^{(k)}}{\sum_{i \in I} a_i^{(k)} c_{ij}} \sum_{i \in E} \frac{c_{ijt}}{\sum_{j' \in J} c_{ij't} \lambda_{j'}^{(k)}}$$

$$\bar{y}_i^{(k+1)} = a_i^{(k)} \sum_{j \in J} c_{ij} \lambda_j^{(k+1)}$$

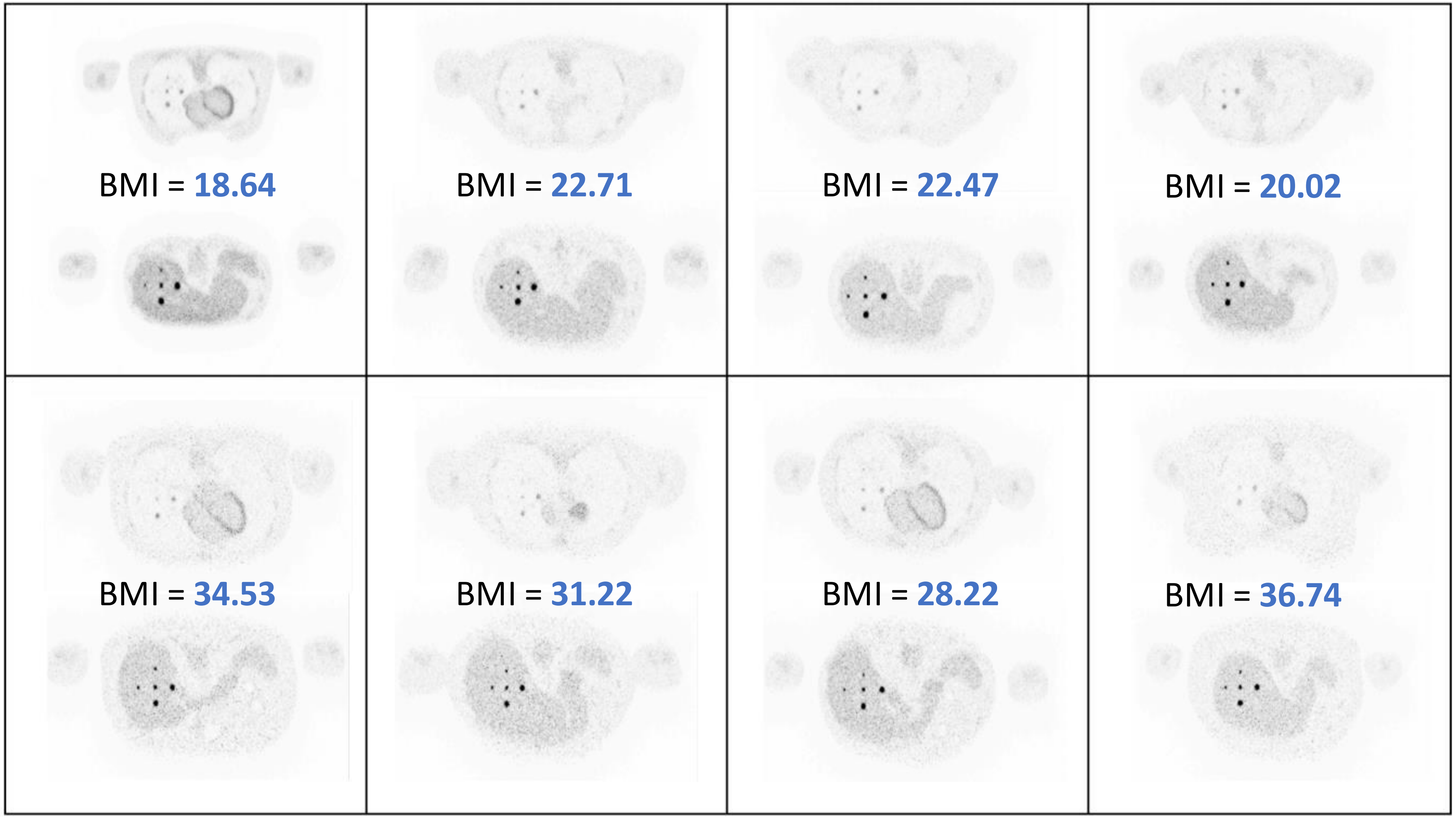
$$\mu_j^{(k+1)} = \mu_j^{(k)} - \frac{\sum_{i \in E} l_{ij} - \sum_{i \in I} l_{ij} \bar{y}_i^{(k+1)}}{\sum_{i \in I} \left(l_{ij} \bar{y}_i^{(k+1)} \sum_{j' \in J} l_{ij'}\right)}$$

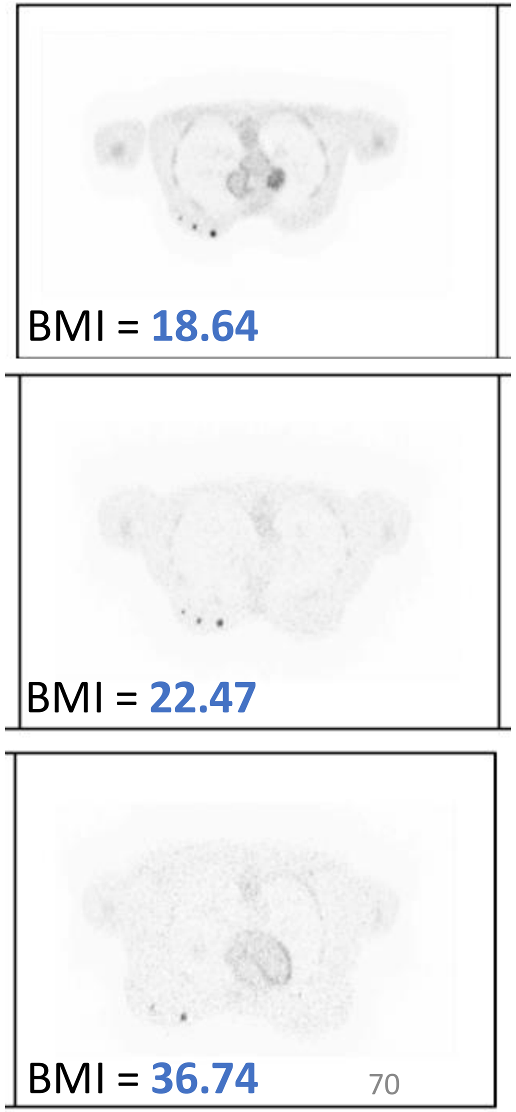
XCAT lesion detectability

Lesion parameters

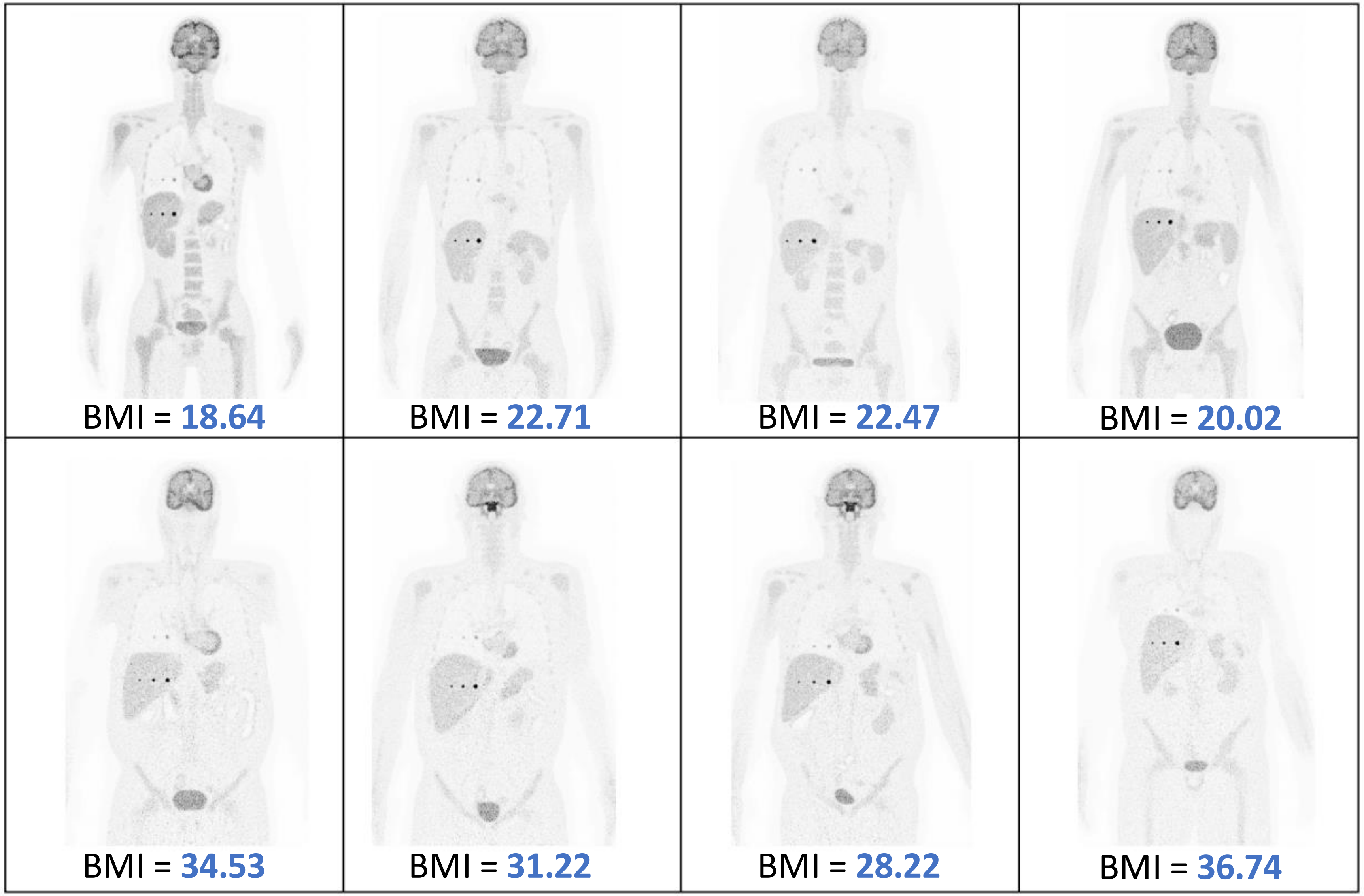
- TBR: 8:1, 4:1, 2:1
  - Only 8:1 shown here
- Lesion size (diameter): 10 mm, 7 mm, 5 mm
- Location: liver, lung, breast

Transverse slices

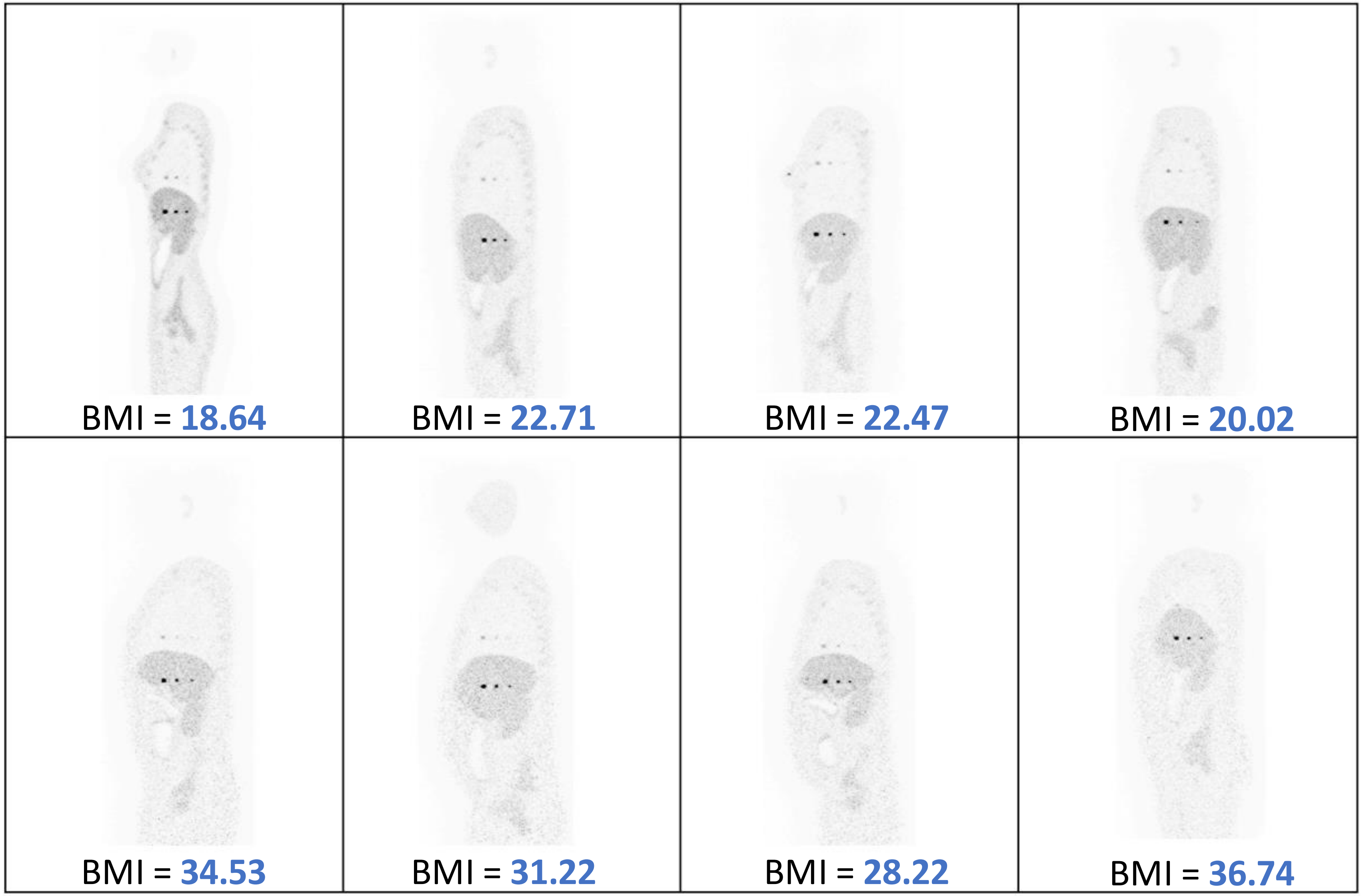




Coronal slices

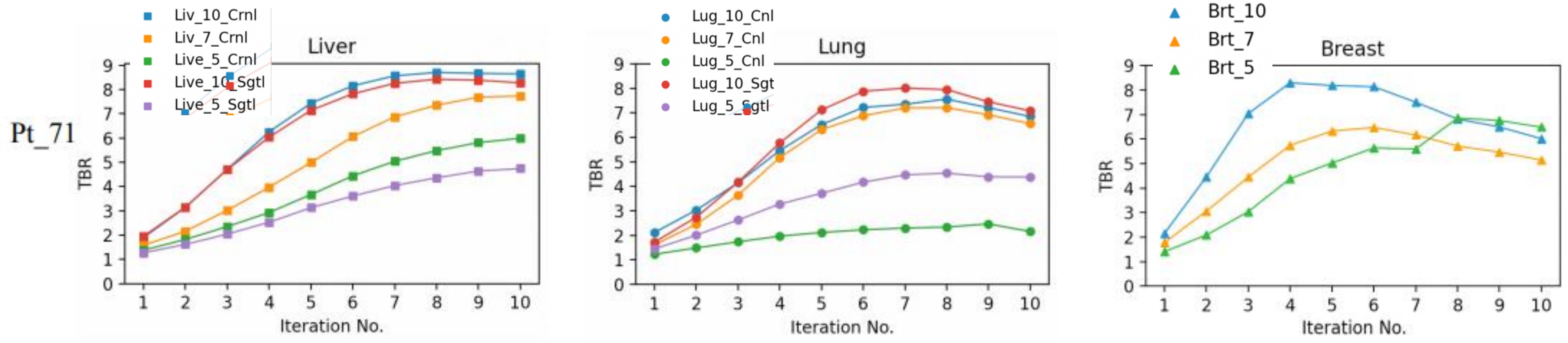


Sagittal slices

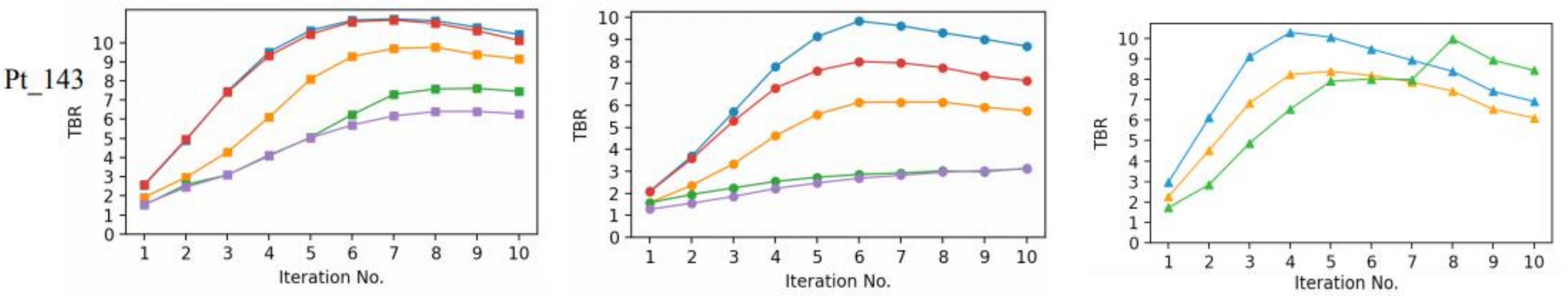


TBR values, female

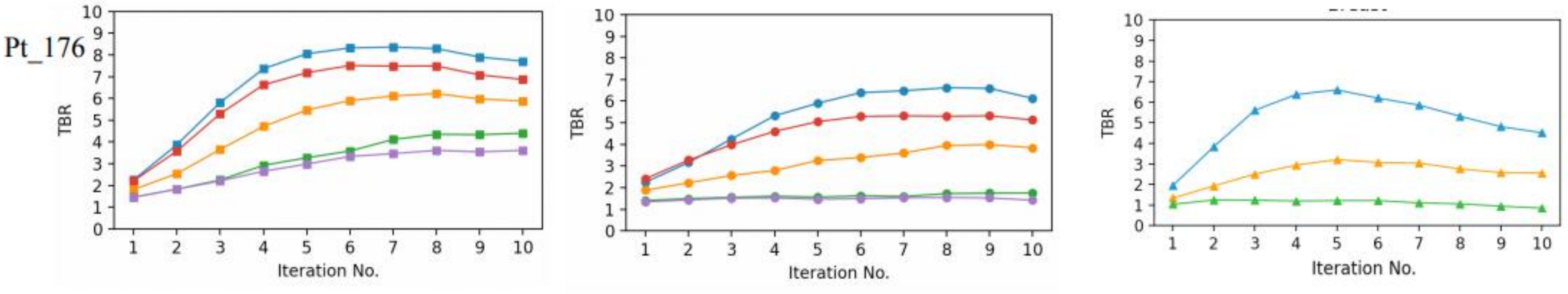
BMI = **18.64**



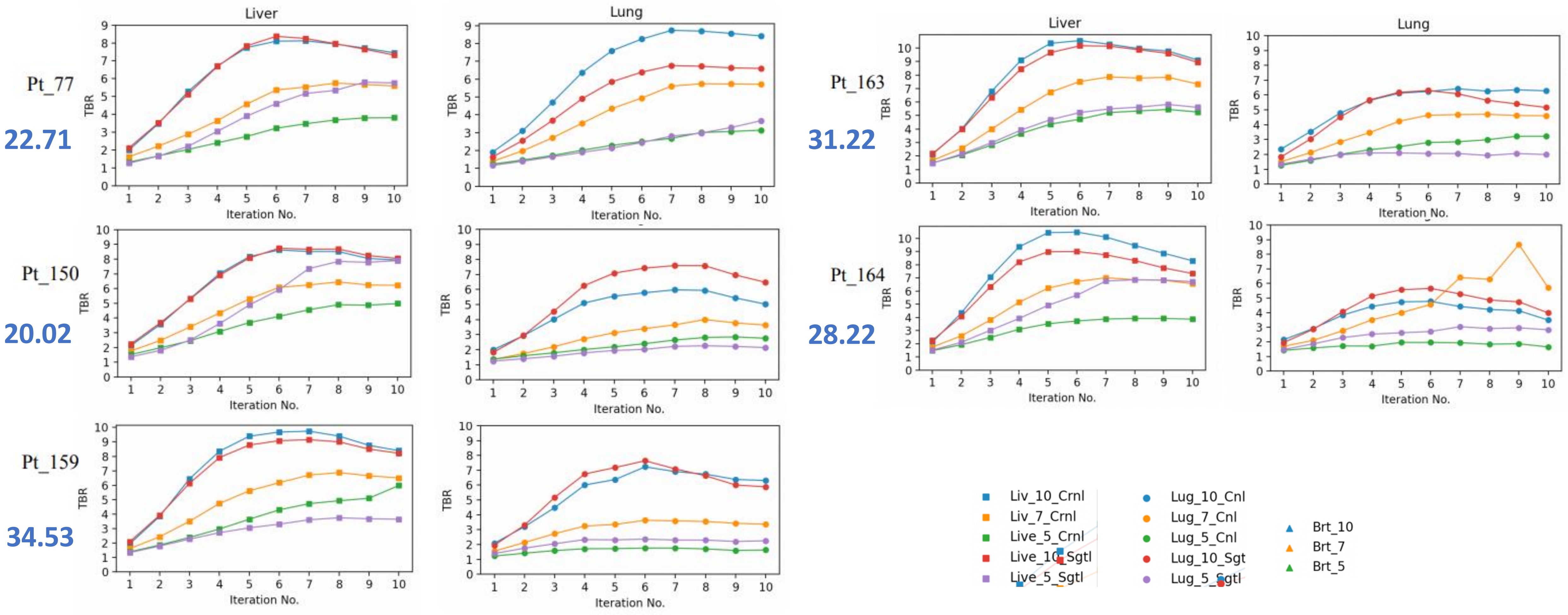
BMI = **22.47**



BMI = **36.74**

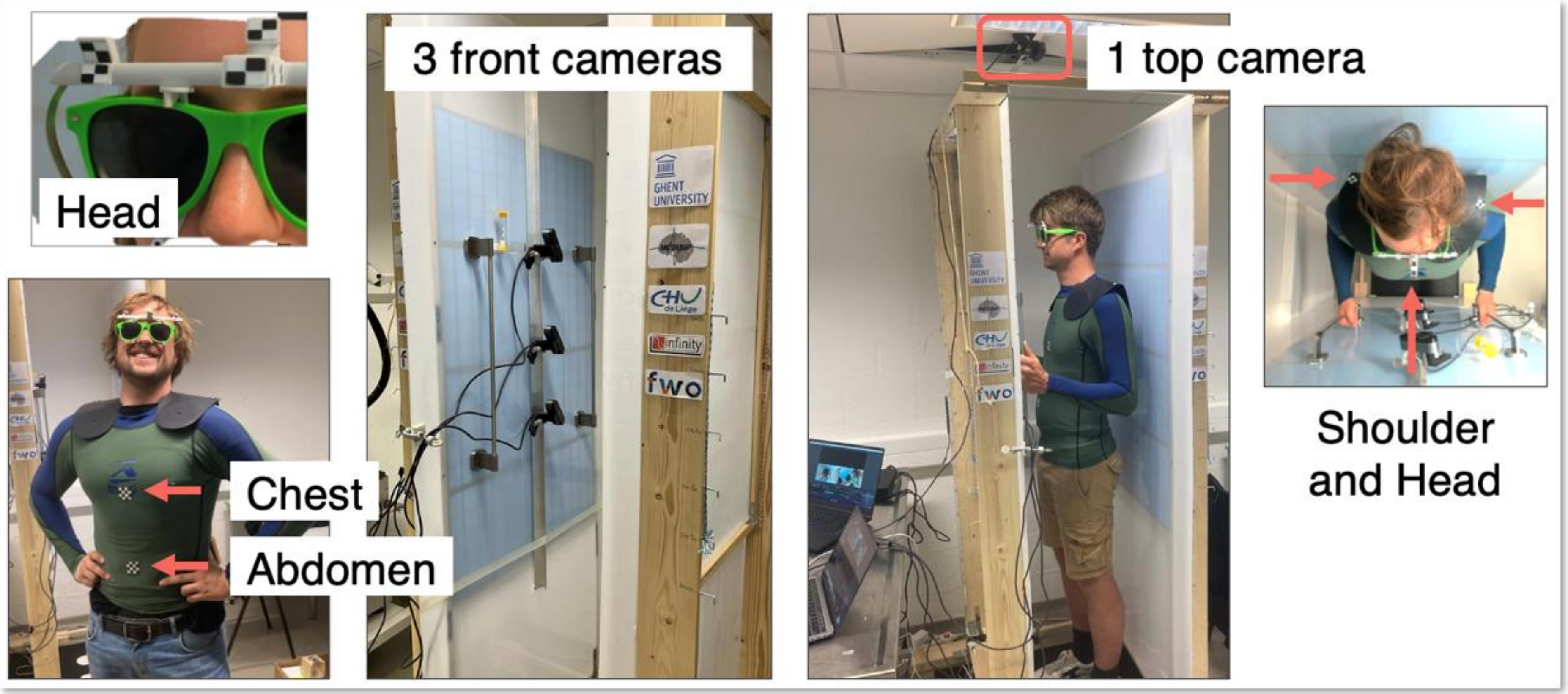


TBR values, male



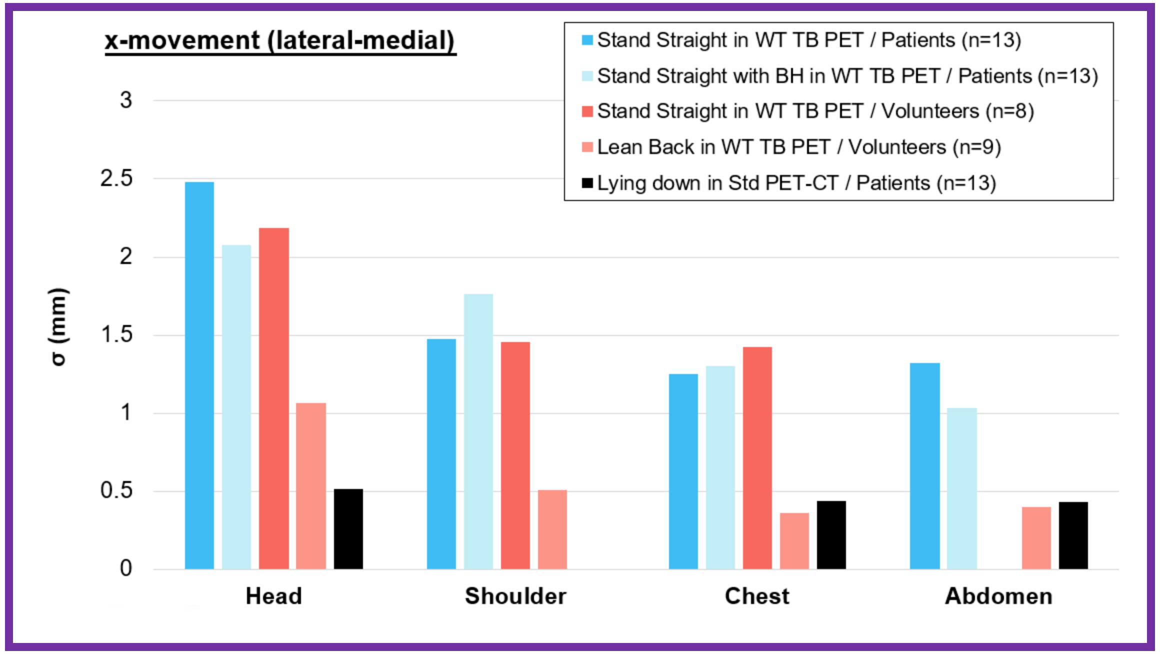
Motion study

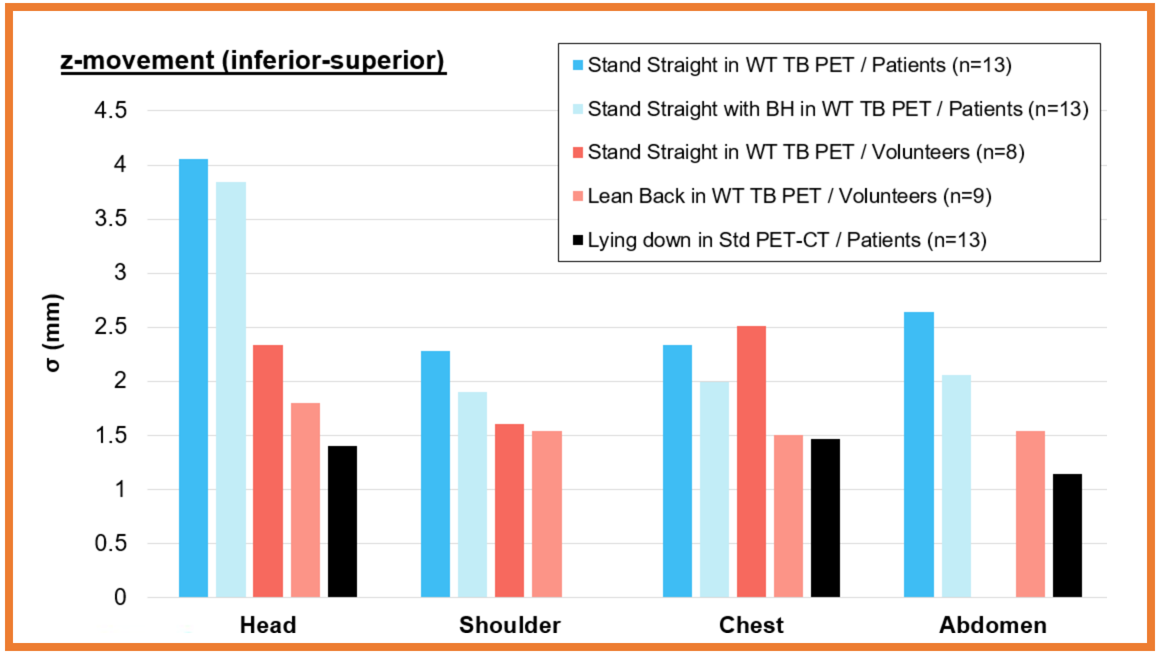
V1: optical cameras

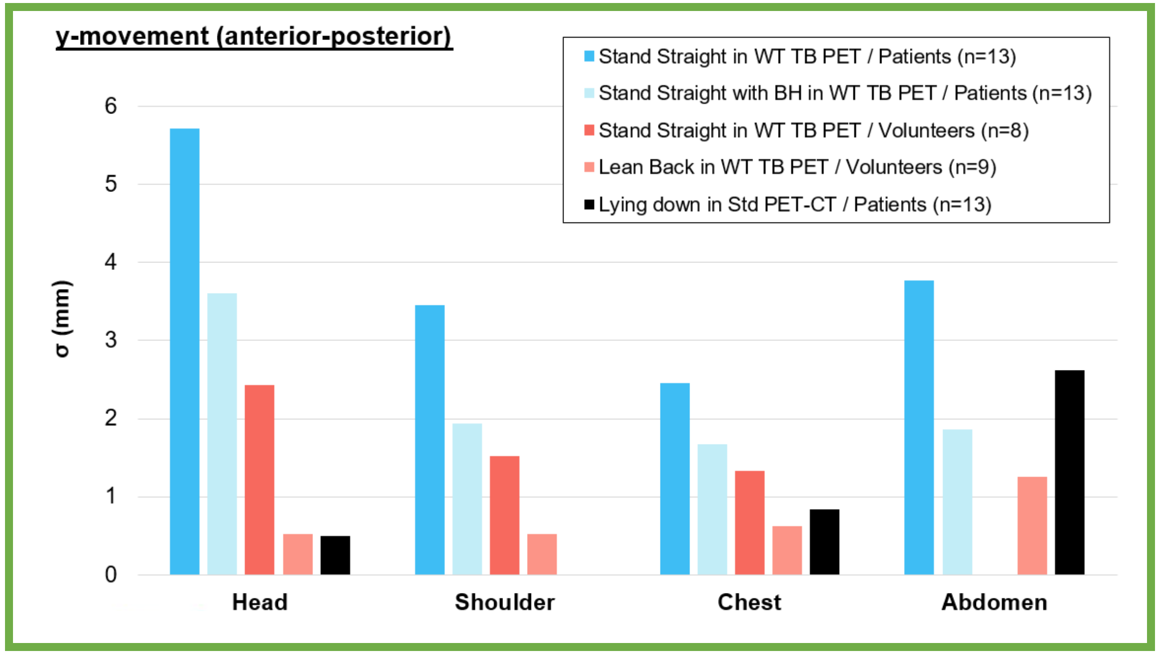


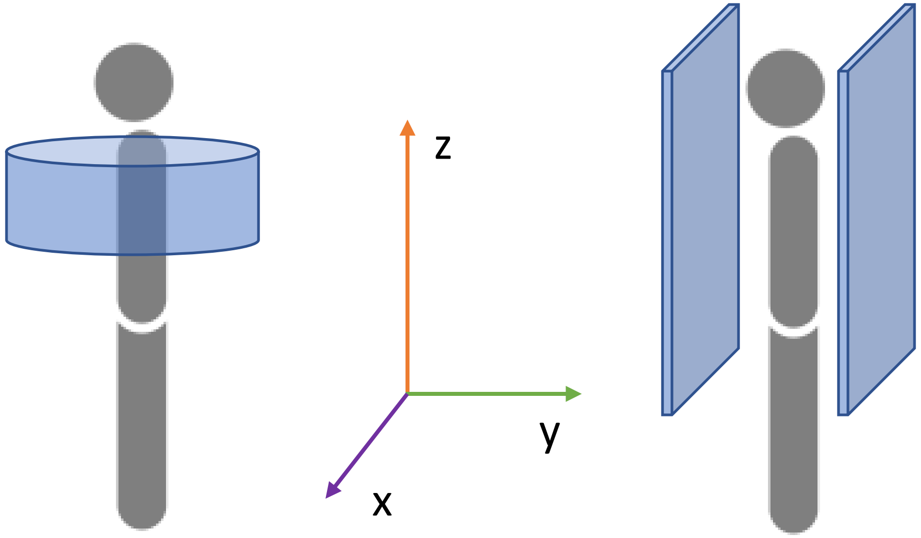
Motion study

V2: Infrared camera


x-movement (lateral-medial)
Stand Straight in WT TB PET / Patients (n=13)
Stand Straight with BH in WT TB PET / Patients (n=13)
Stand Straight in WT TB PET / Volunteers (n=8)
Lean Back in WT TB PET / Volunteers (n=9)
Lying down in Std PET-CT / Patients (n=13)
σ (mm)
0
0.5
1
1.5
2
2.5
3
Head
Shoulder
Chest
Abdomen


z-movement (inferior-superior)
Stand Straight in WT TB PET / Patients (n=13)
Stand Straight with BH in WT TB PET / Patients (n=13)
Stand Straight in WT TB PET / Volunteers (n=8)
Lean Back in WT TB PET / Volunteers (n=9)
Lying down in Std PET-CT / Patients (n=13)
σ (mm)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Head
Shoulder
Chest
Abdomen


y-movement (anterior-posterior)
Stand Straight in WT TB PET / Patients (n=13)
Stand Straight with BH in WT TB PET / Patients (n=13)
Stand Straight in WT TB PET / Volunteers (n=8)
Lean Back in WT TB PET / Volunteers (n=9)
Lying down in Std PET-CT / Patients (n=13)
σ (mm)
0
1
2
3
4
5
6
Head
Shoulder
Chest
Abdomen


z
y
x

Motion artefact reduction

1. Reduce motion as much as possible

2. Correct for motion during reconstruction