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Current features and technological advances

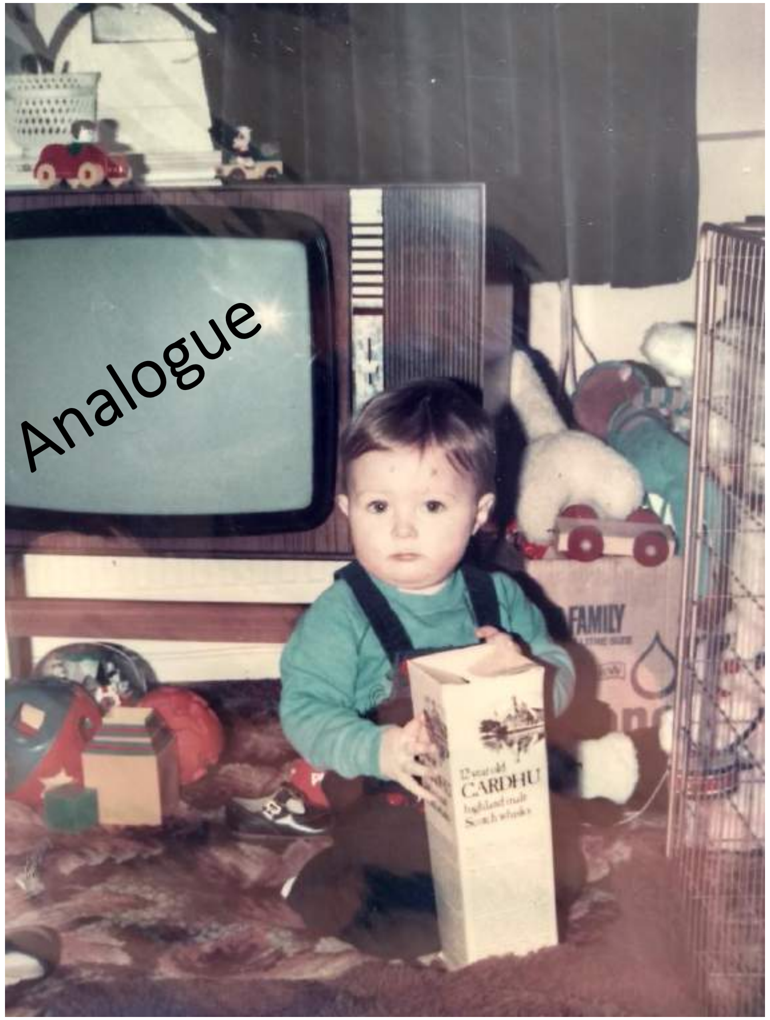
Dr Ian Armstrong

Principal Physicist

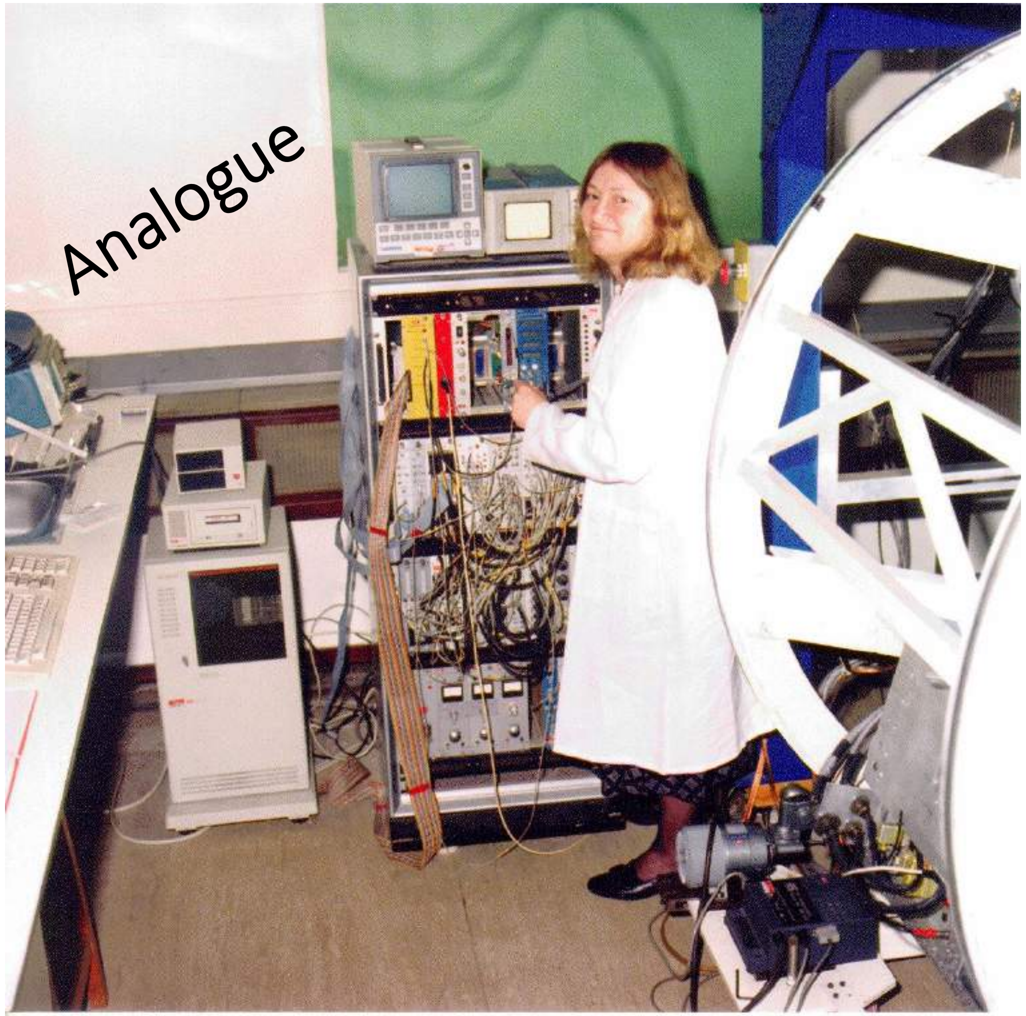
Nuclear Medicine Centre
Manchester University NHS Foundation Trust

IPEM Introduction to PET : 24th – 25th May 2021

Analogue PET????



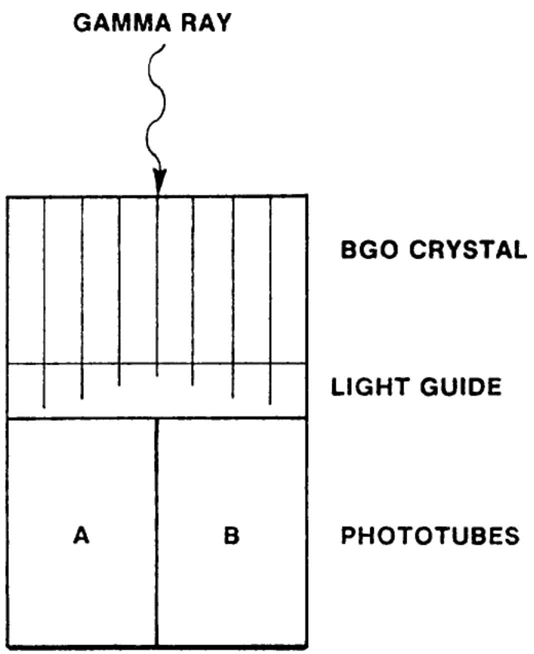
Armstrong household c1983



University of Birmingham.
Courtesy Peter Julyan

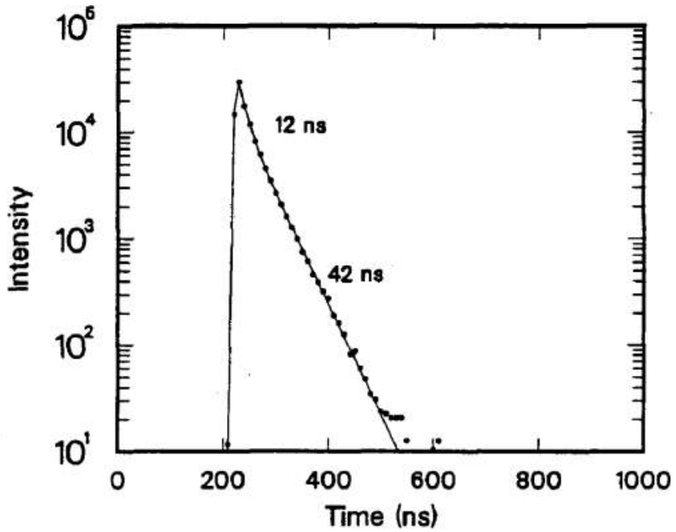
The building blocks of traditional PET

Block detector



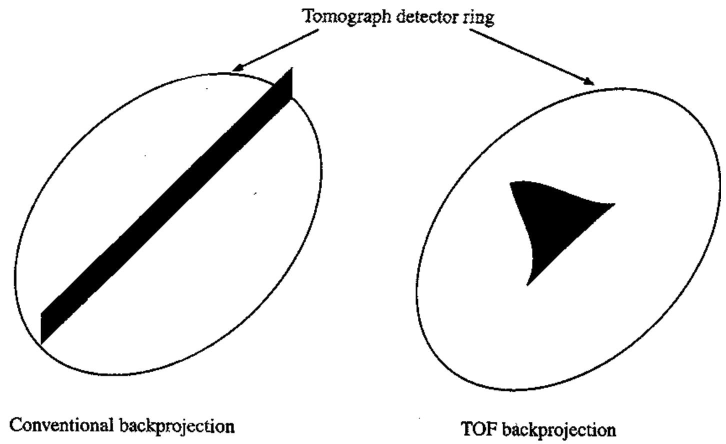
Casey & Nutt 1986
Trans Nucl Sci **33**:460

LSO crystals



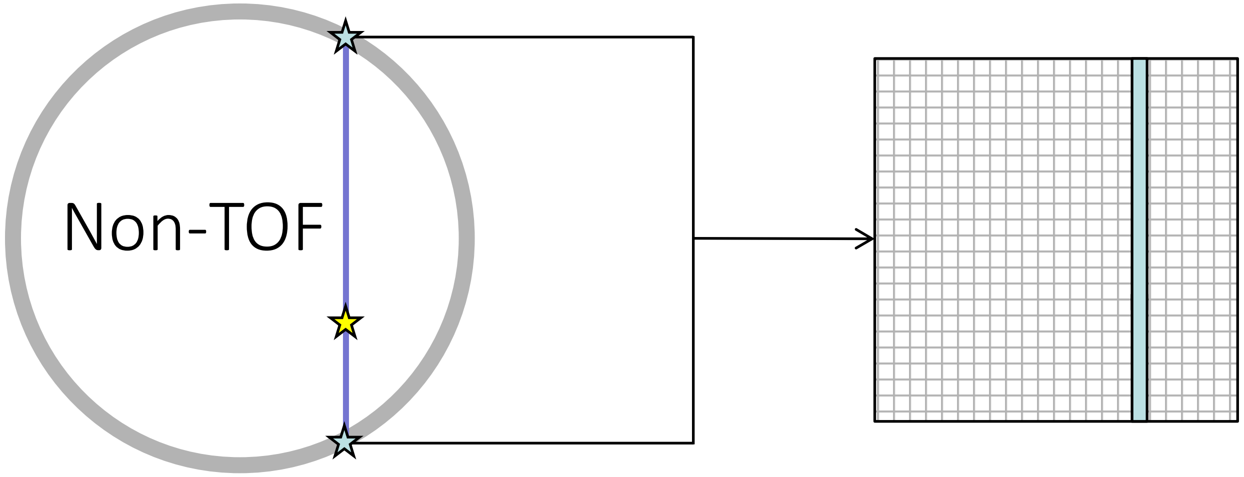
Melcher & Schweitzer 1992
Trans Nucl Sci **39**:502

Time-of-Flight

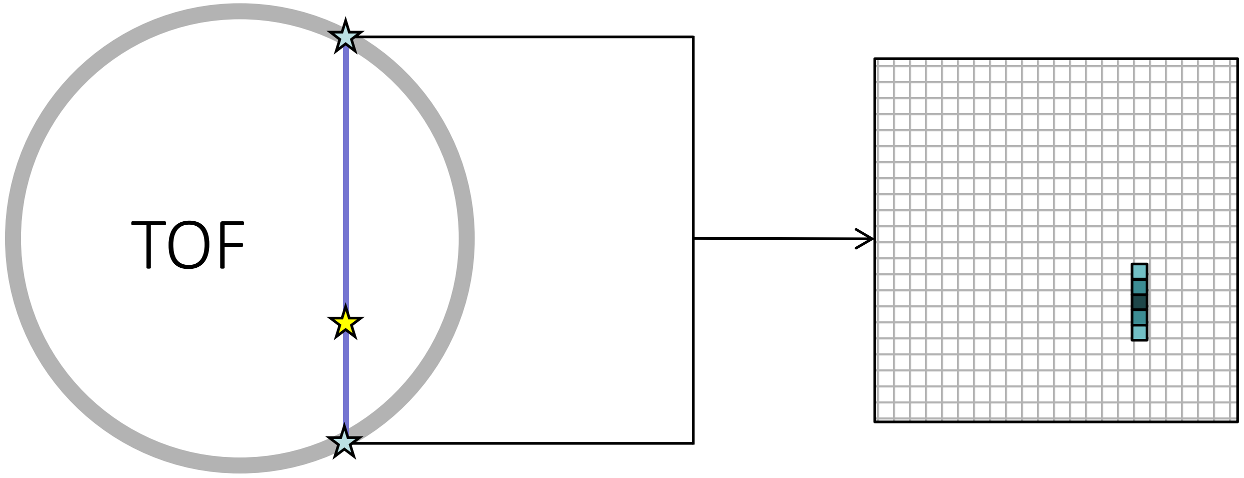


Lewellen 1998
Sem Nucl Med **28**:268

Time-of-Flight



Without TOF, no information of whereabout annihilation occurred on line of response



TOF allows for estimation of location of annihilation event

Gain in SNR with TOF

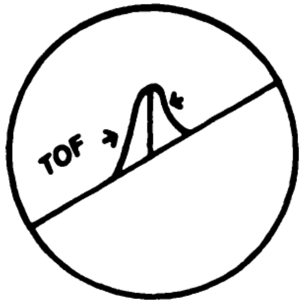
$$SNR_{gain} = \sqrt{\frac{D}{\Delta x}}$$

$$NEC_{gain} = \frac{D}{\Delta x}$$

sensitivity gain

can derive "effective sensitivity"

Assumes positional uncertainty is top-hat function when in reality is Gaussian



$$NEC_{gain} \cong \frac{1}{1.6}\frac{D}{\Delta x}$$

Gain is not as large

Wong *et al*. *J Nucl Med* 1983; **24**:52-60
Conti *et al*. *IEEE Nucl Sci Symp Conf Rec*. 2011; 2470-14

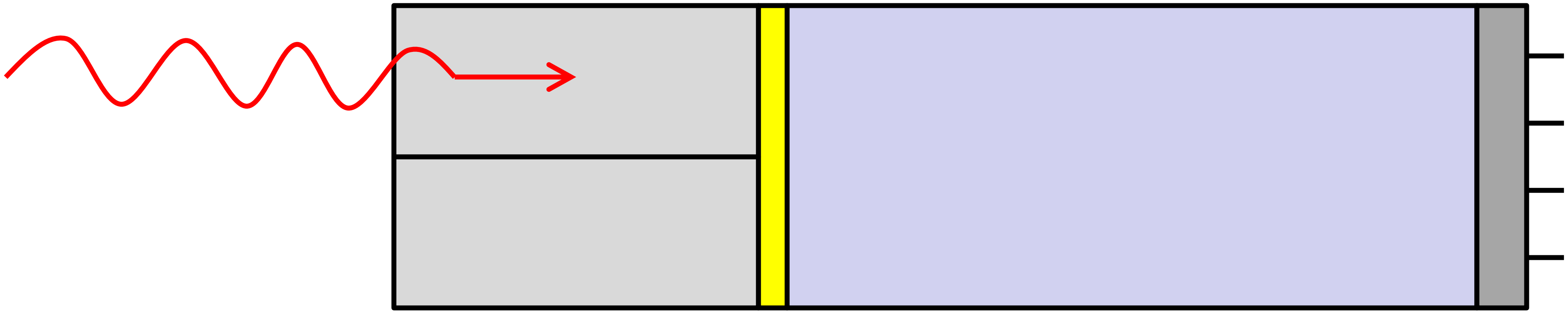
Effective TOF sensitivity

- TOF improves SNR (not spatial resolution!)
- Gives the effect of increased sensitivity
- Can define effective sensitivity S_{eff}, which is dependent on
  - object size D
  - intrinsic sensitivity S_{int}
  - annihilation positional uncertainty due to TOF **Δx**

$$S_{eff} = S_{int} \times \frac{1}{1.6} \times \frac{D}{\Delta x}$$

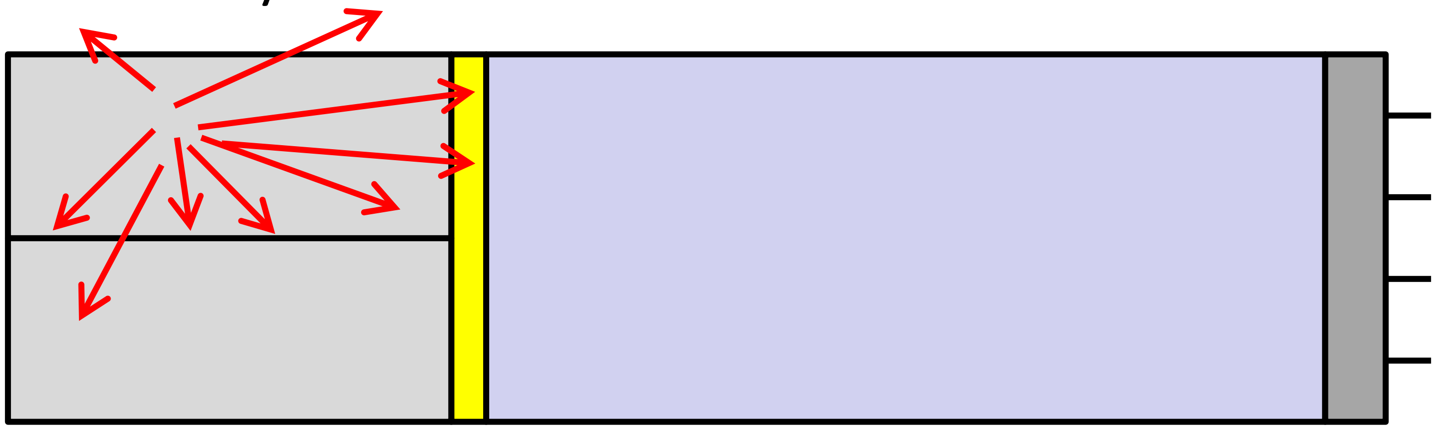
$$\Delta \mathrm{x} = \frac{\mathrm{c}\Delta \mathrm{t}}{2}$$

PET detectors



511 keV photon is absorbed in scintillation crystal

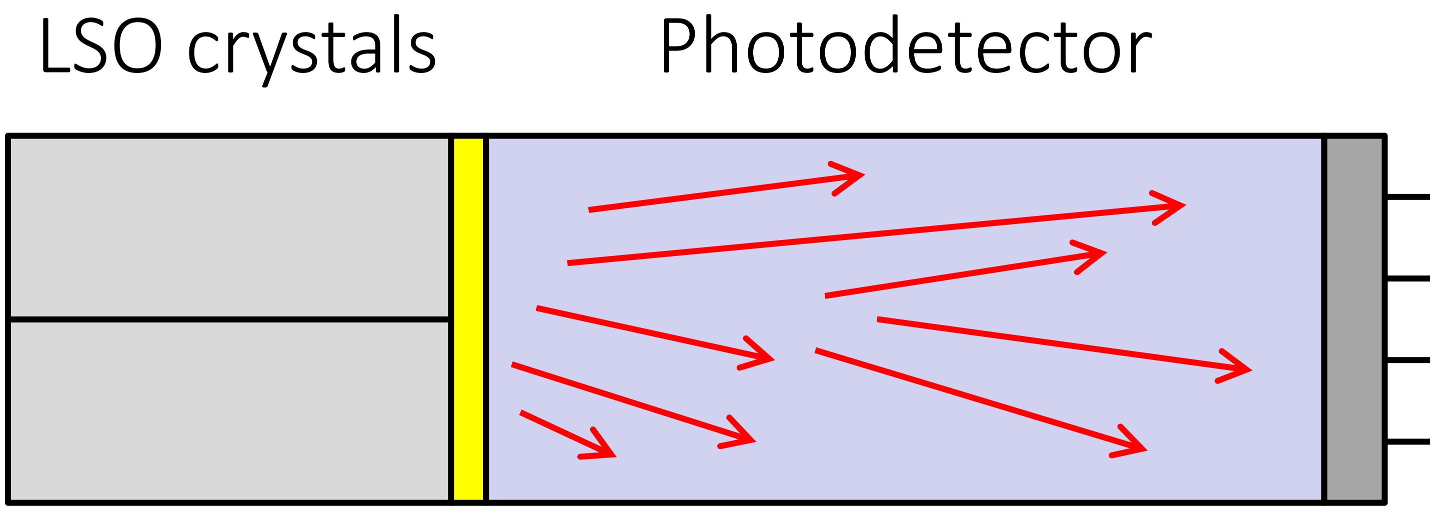
PET detectors



Several thousand optical photons are produced in the scintillation crystal

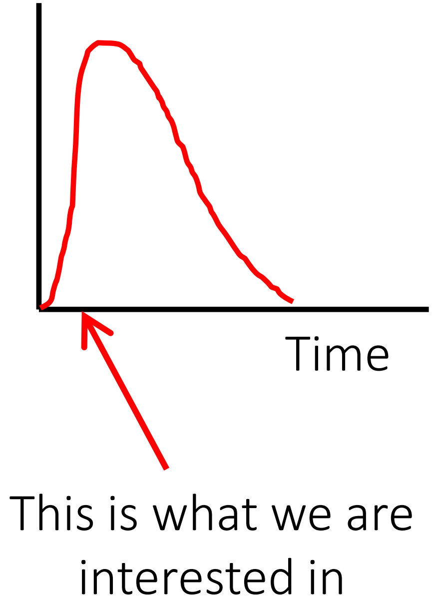
Some of these will propagate through the crystal towards the photodetector

PET detectors



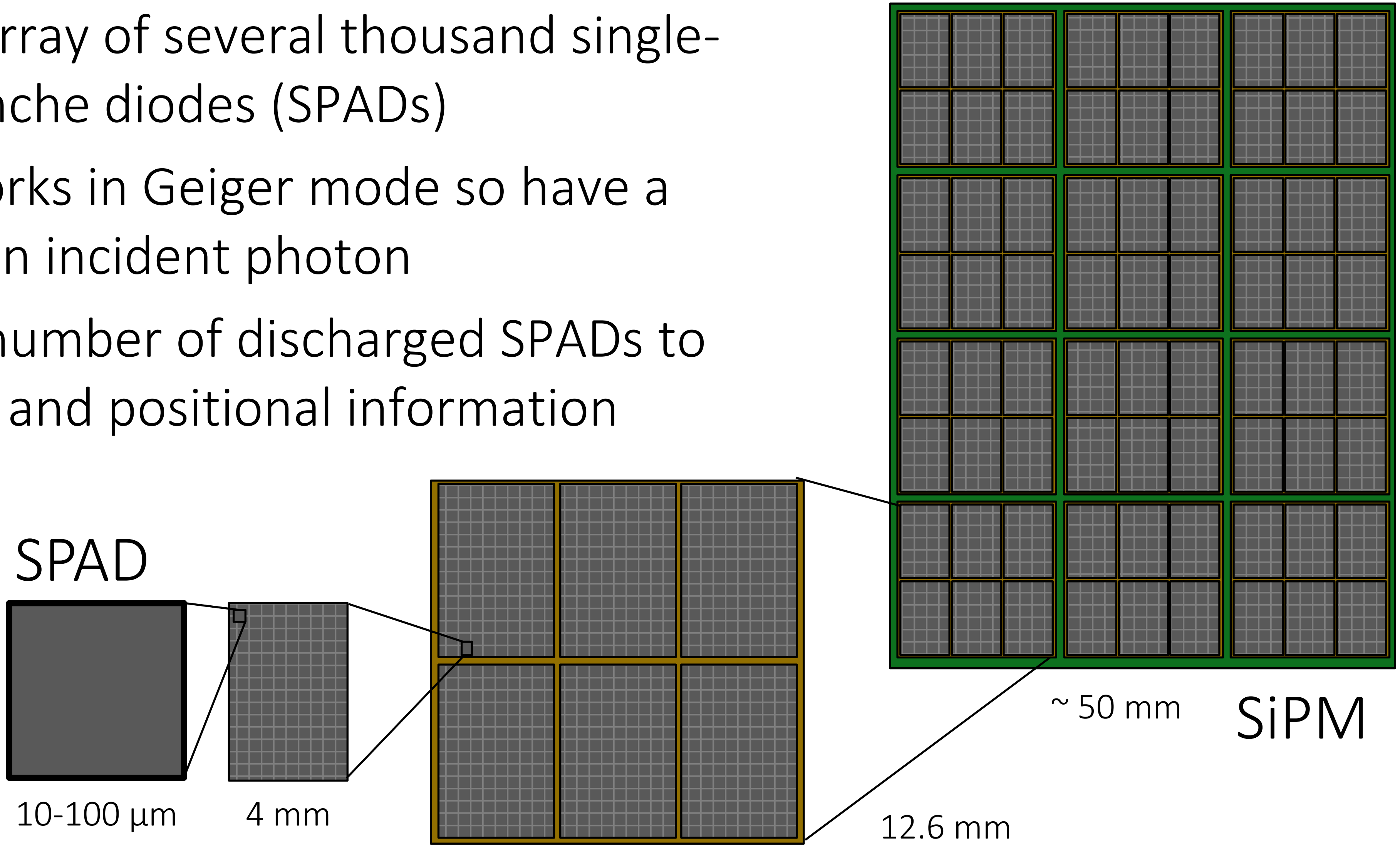
The optical photons arrive over a finite time range at photodetector

Photodetector converts the optical photons into an electrical charge



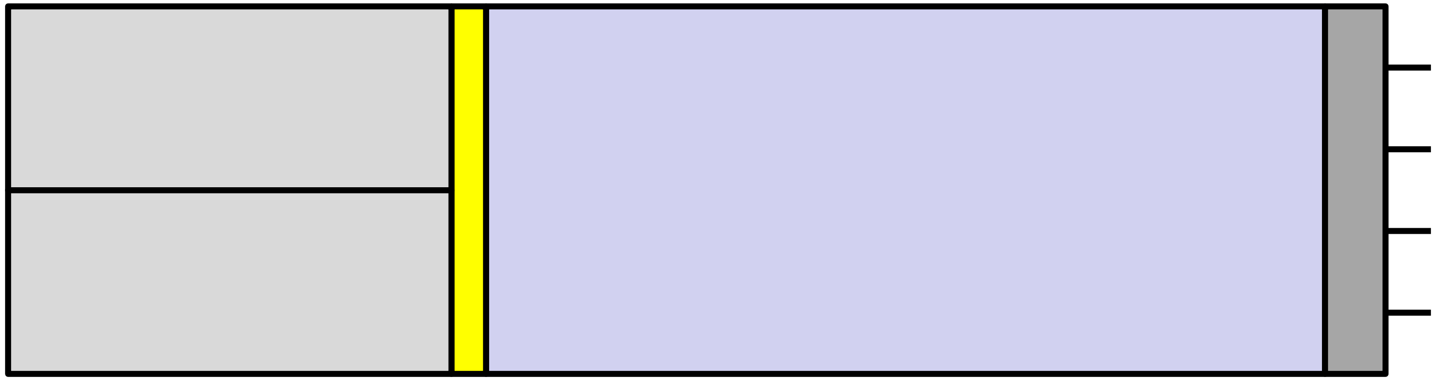
Silicone Photomultiplier (SiPM)

- A SiPM is an array of several thousand single-photon avalanche diodes (SPADs)
- Each SPAD works in Geiger mode so have a discharge upon incident photon
- Can sum the number of discharged SPADs to derive energy and positional information

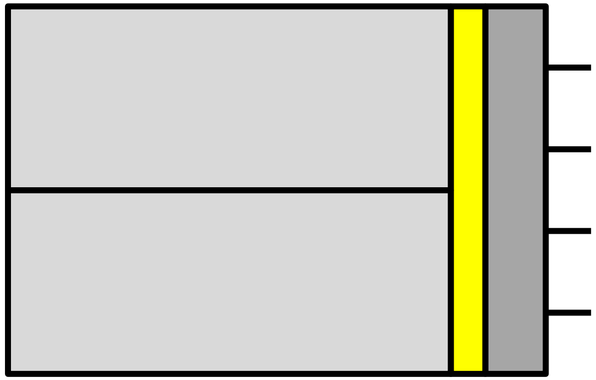


Photodetectors: photomultiplier vs SiPM

- Traditional photomultiplier tubes (PMT) have relatively low quantum efficiency (around 25%)
- Quantum efficiency for SiPM is greater (around 35 to 40%)
- PMTs have single-photon timing jitter of few hundred picoseconds to nanoseconds
- SiPMs have typical single-photon timing jitter of 100 to 200 ps



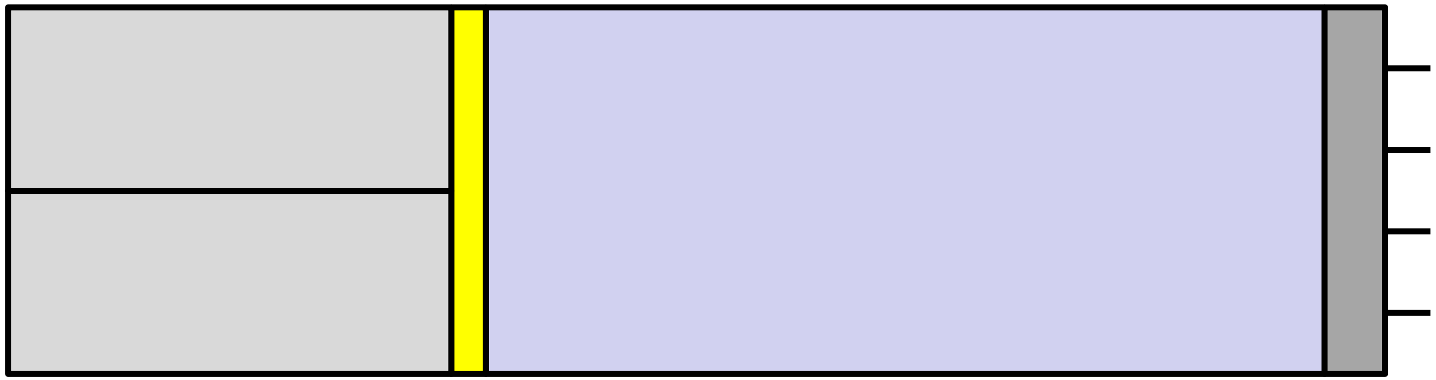
Scintillator + PMT



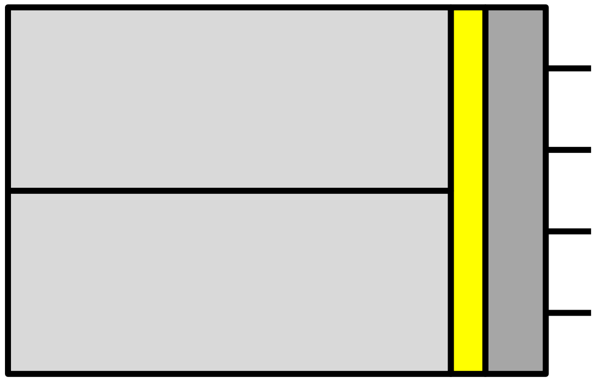
Scintillator + SiPM

Photodetectors: photomultiplier vs SiPM

- These two characteristics means that SiPM have a superior ability to measure the arrival time of the 511 keV photons
- Superior performance for Time-of-Flight PET
- Still have the scintillator crystal



Scintillator + PMT



Scintillator + SiPM

PET-CT comparison

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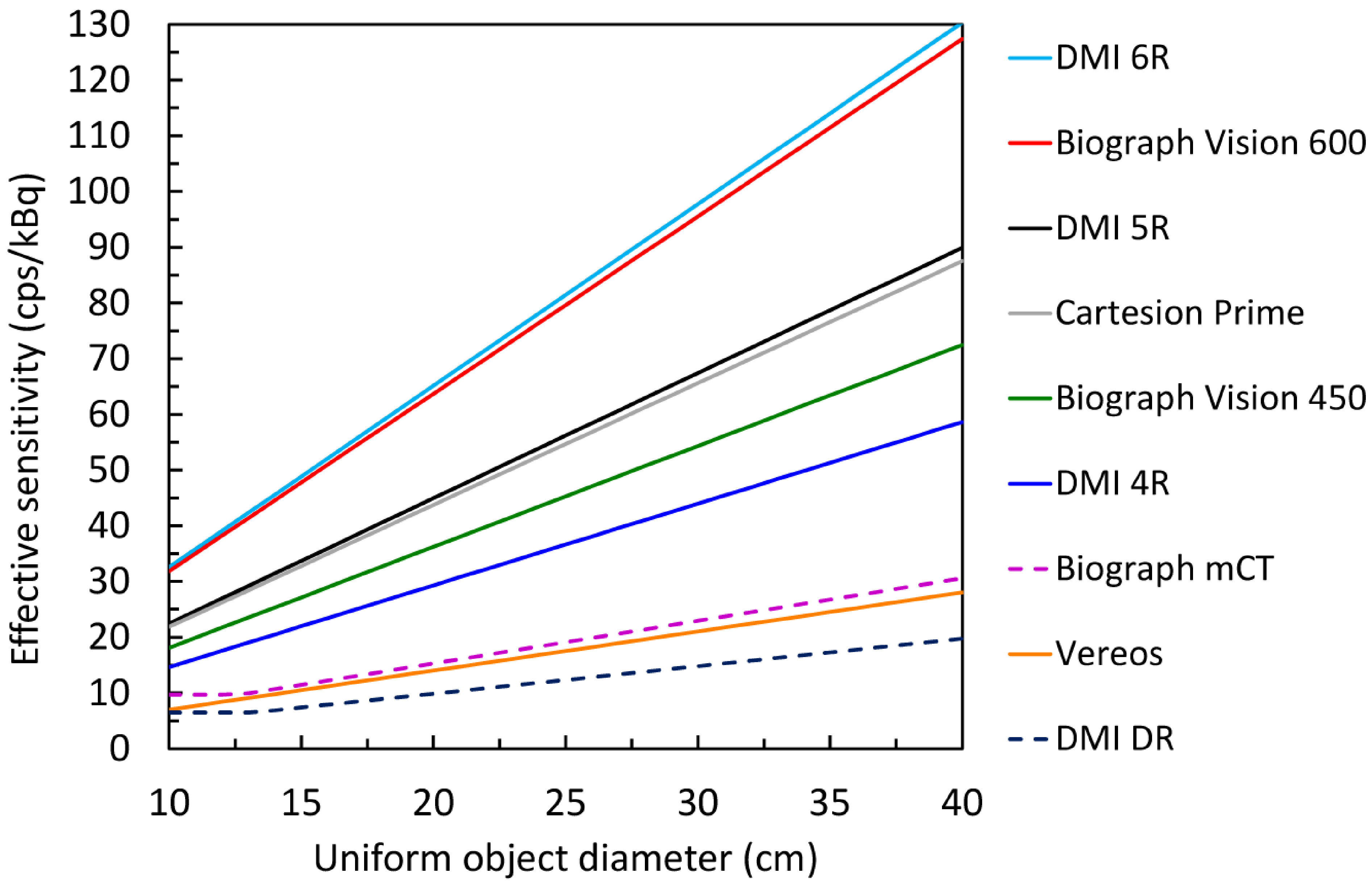
System	Detector	Intrinsic Sensitivity (cps/kBq)	TOF Res (ps)	NEMA Performance Reference
Biograph mCT	PMT	9.7	530	Jakoby 2011
Discovery MI DR	PMT	6.5	550	Chicheportiche 2020
Biograph Vision 450	SiPM	9.1	215	Carlier 2020
Biograph Vision 600	SiPM	16	215	Sluis 2019
Cartesion Prime	SiPM	13.5	258	Not available yet
Discovery MI 4R	SiPM	13.5	385	Chicheportiche 2020
Discovery MI 5R	SiPM	20.7	385	Pan 2019
Discovery MI 6R	SiPM	30.0	385	Not available yet
Vereos	SiPM	5.2	310	Rausch 2019

PET-CT TOF effective sensitivity



The future of TOF…

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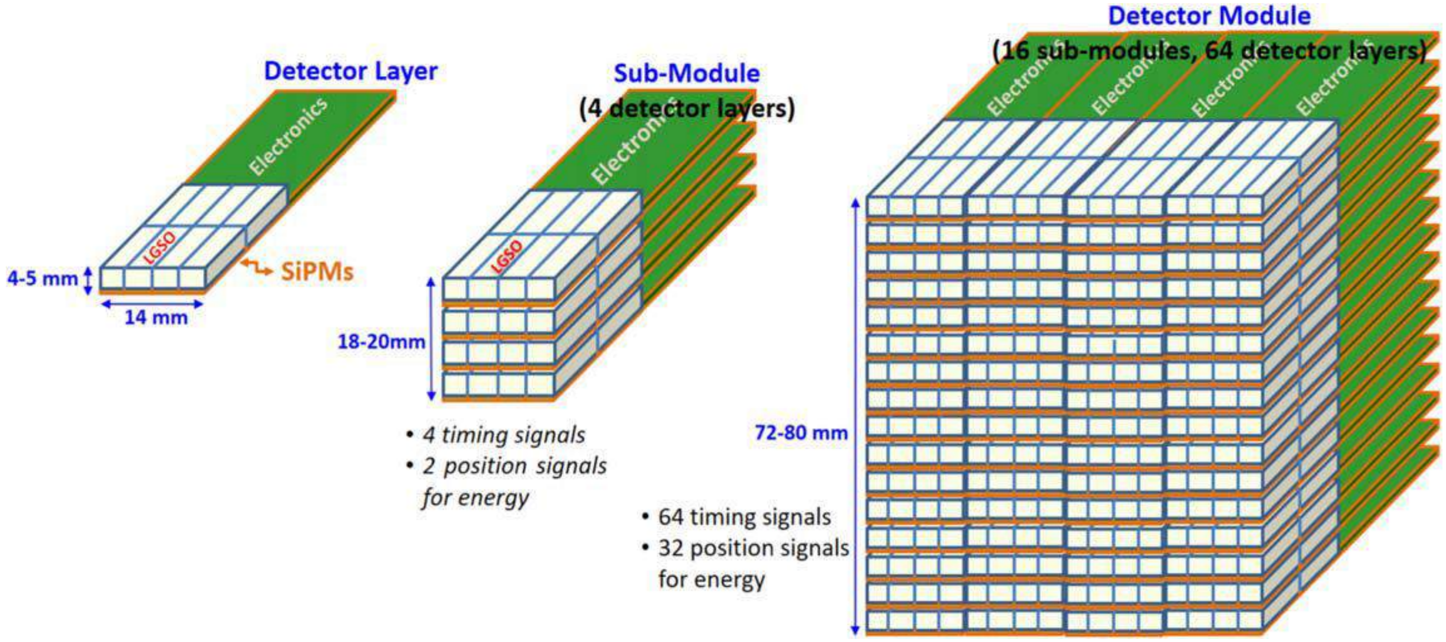
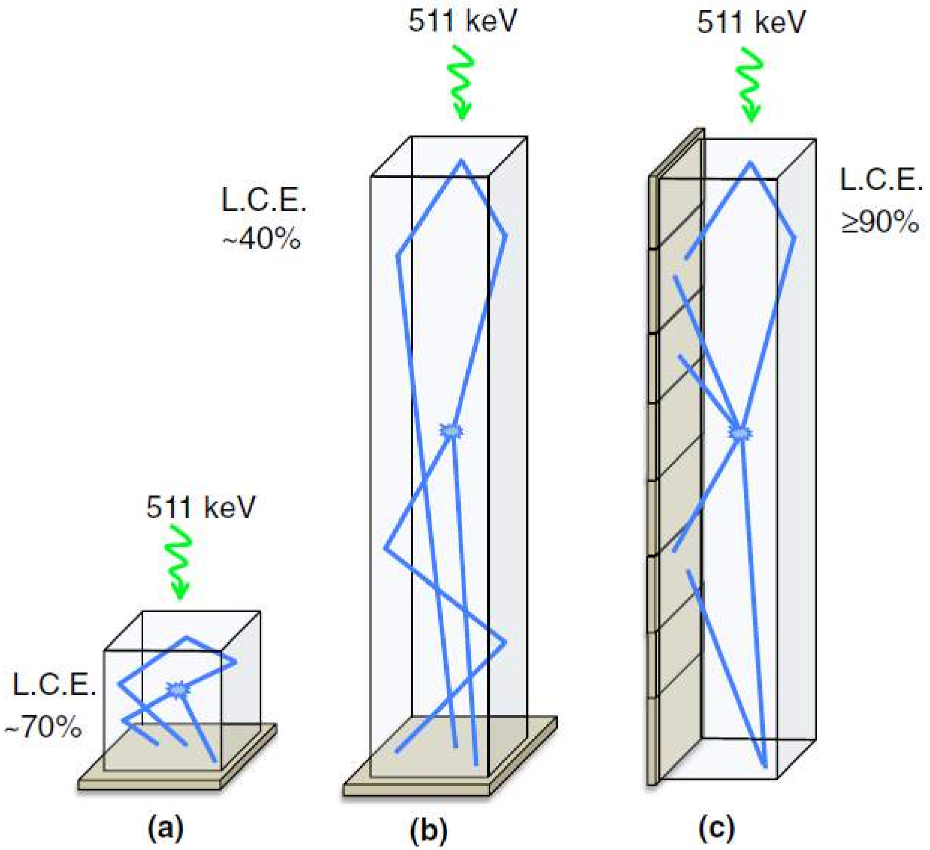
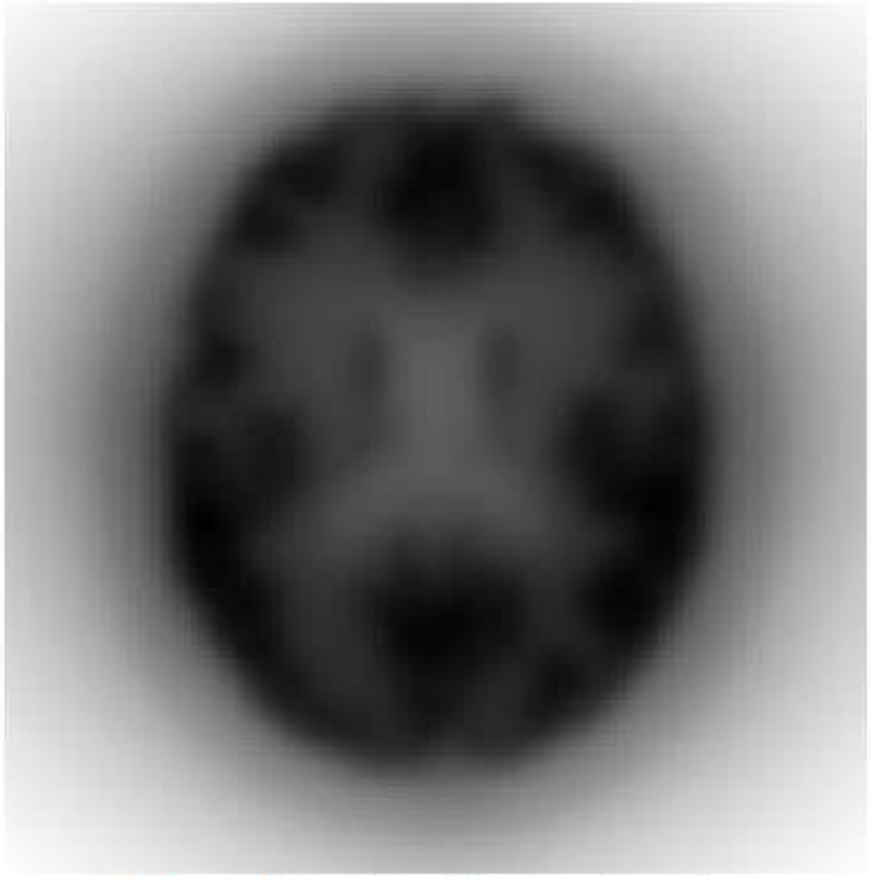




- 100 ps TOF seen as "the next goal"
- Active area looking at detector design
- Alternative scintillators

Cates and Levin. *Phys Med Biol* 2018; **63**:115011
Pourashraf *et al*. *Phys Med Biol* 2021; **66**:085005

And then the future future...

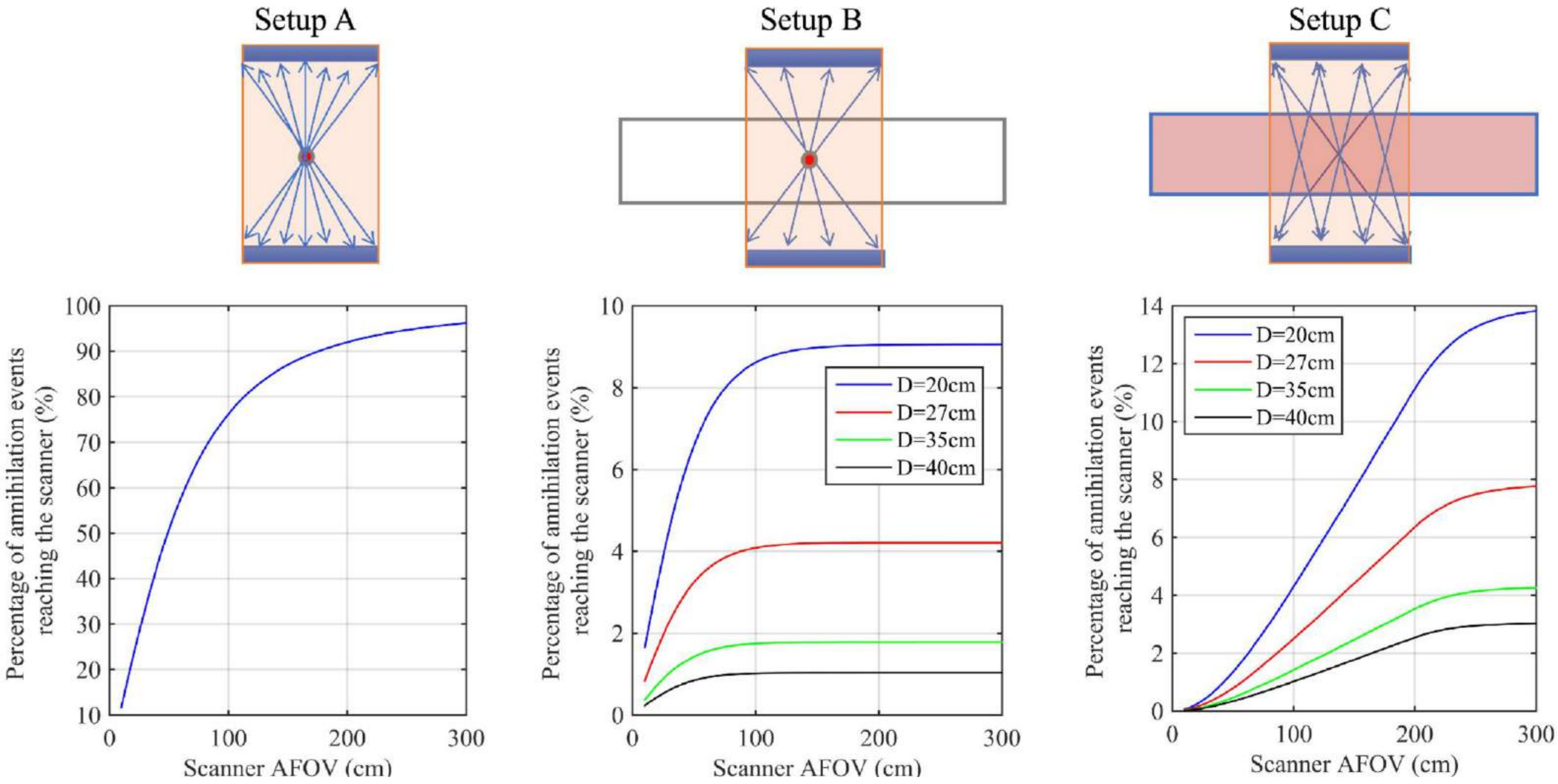


Non-TOF back-projection

TOF back-projection with 10 ps FWHM CTR

https://the10ps-challenge.org

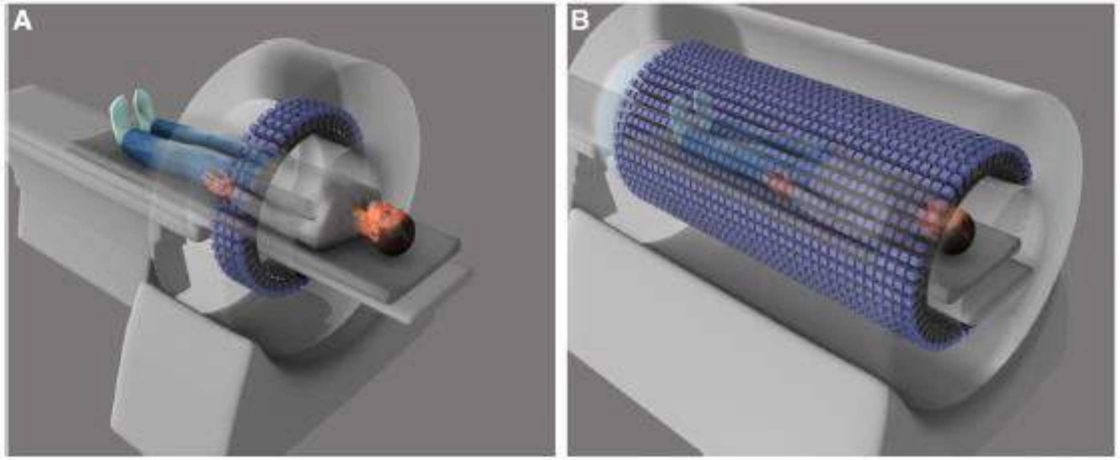
Geometric efficiency



Surti 2020; *IEEE Trans Rad Plasma Med Sci*

“Total-body” LAFOV systems

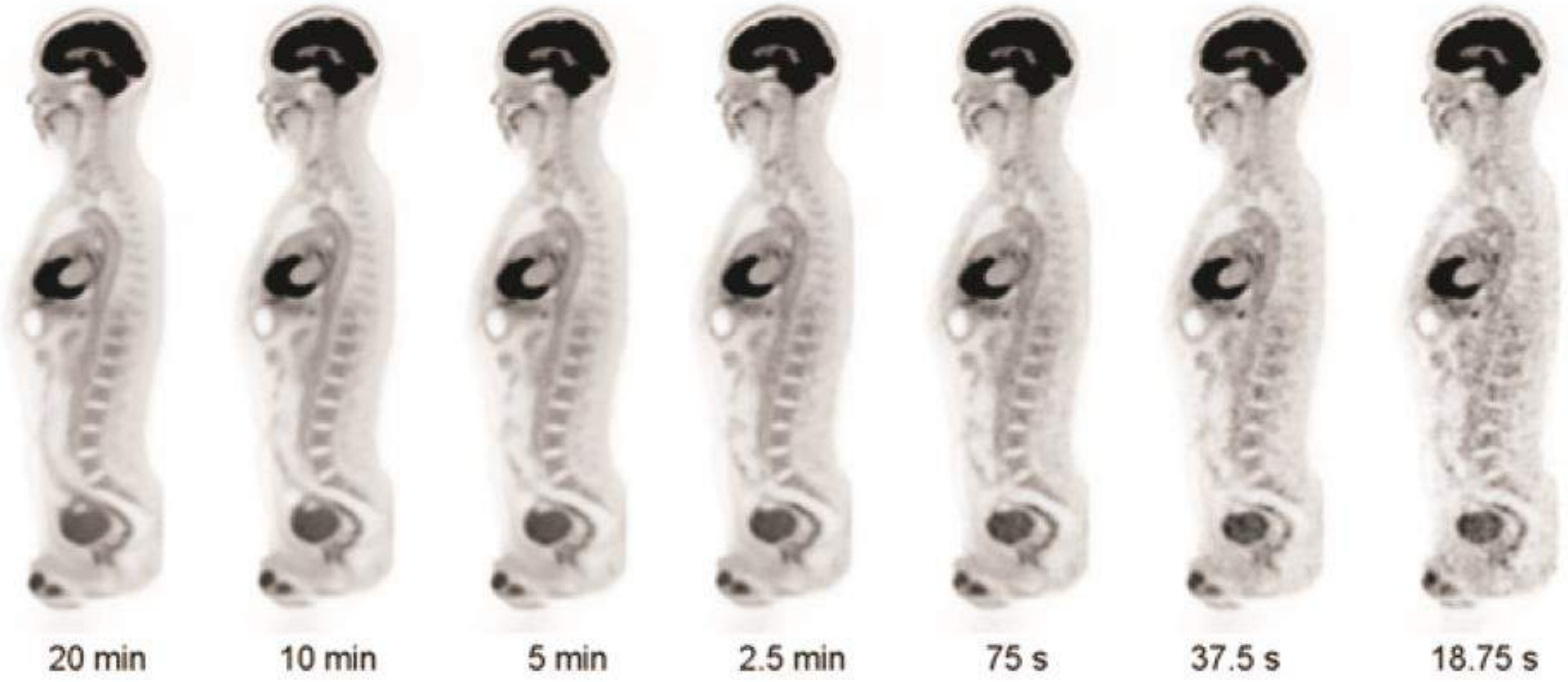
- EXPLORER
  - 194 cm AFOV
  - SiPM : 430 ps TOF
- PennPET Explorer
  - 64 cm AFOV
  - SiPM : 249 ps
- Siemens Biograph Quadra
  - 106 cm AFOV
  - SiPM : 220 ps



Cherry 2018 *J Nucl Med* **59**:3-12

Karp 2020 *J Nucl Med* **61**:136-43

Benefits of LAFOV systems



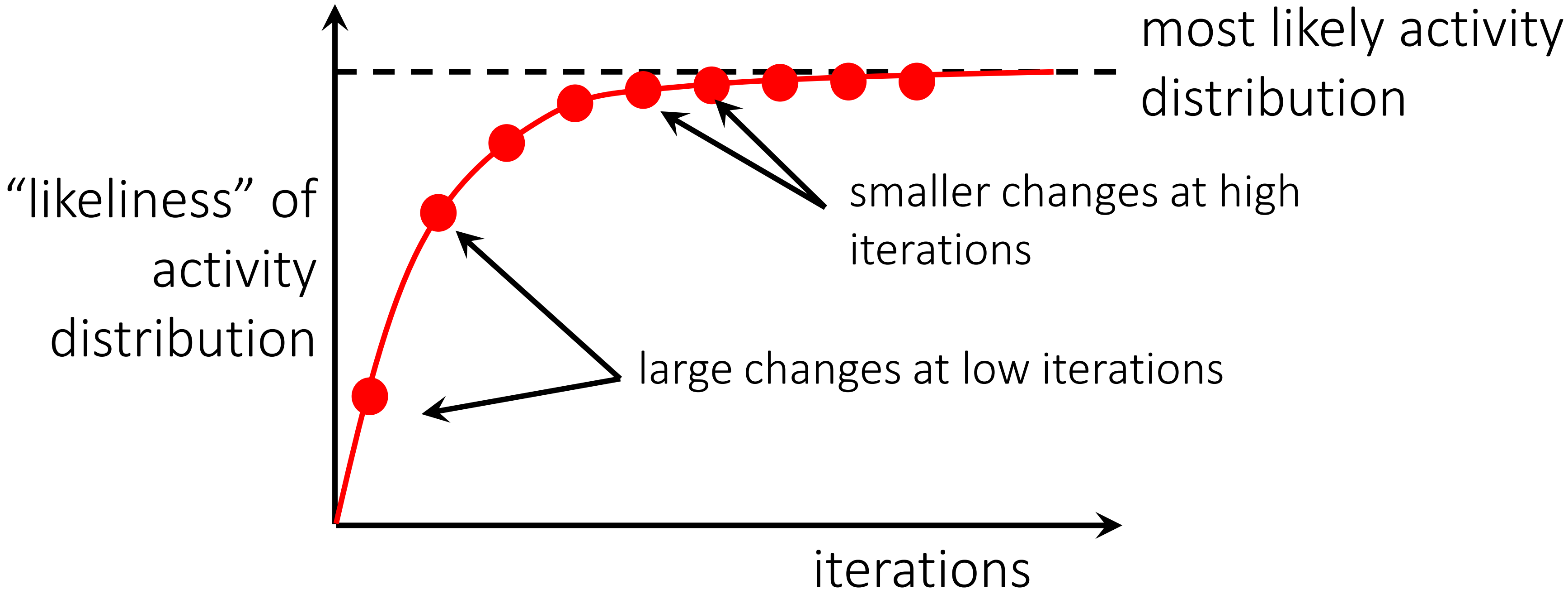
EXPLORER

Badawi *J Nucl Med* 2019; **60**:299-303

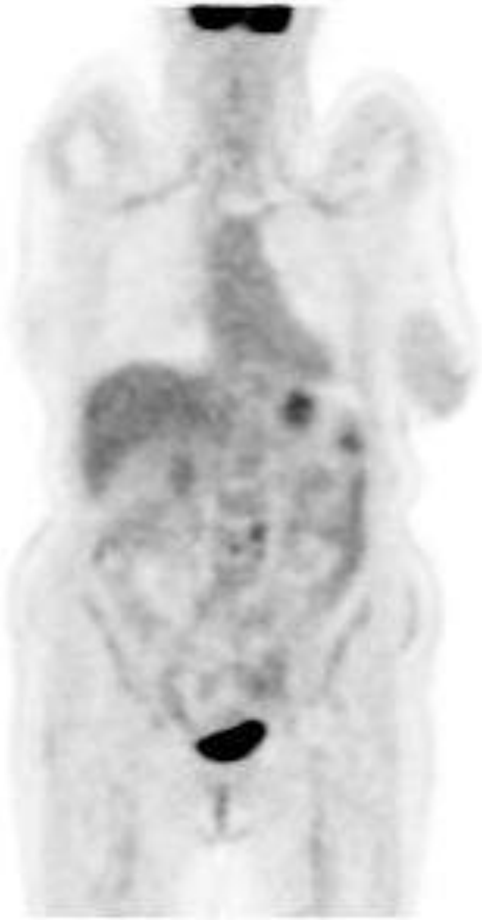
Improvements to detectors

- The increased sensitivity (intrinsic and effective) reduces requirement for post-reconstruction smoothing to control noise
- Detector design (smaller crystals) produces higher-resolution images
- Reconstruct into small voxels
- All this leads to improved image quality and increase visualisation of small lesions

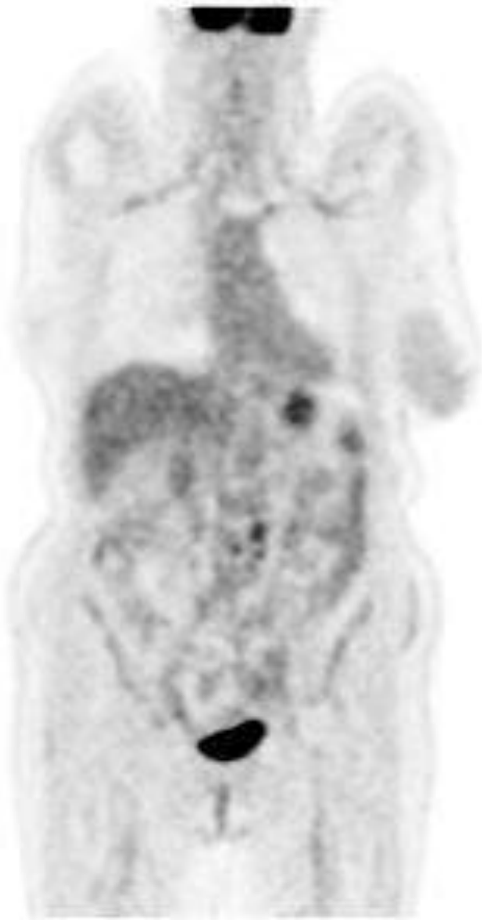
- Iterative reconstruction produces an estimate of activity distribution
- The estimate of the activity distribution is said to **converge** to the most likely activity distribution
- At convergence, more iterations does not change estimate



But a problem is noise!



1 iteration



2 iterations

15 iterations

25 iterations

Images courtesy of Ian Croasdale, GE Healthcare

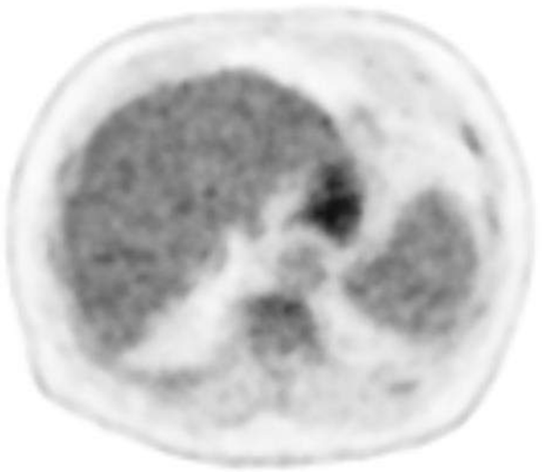
Reconstruction algorithms

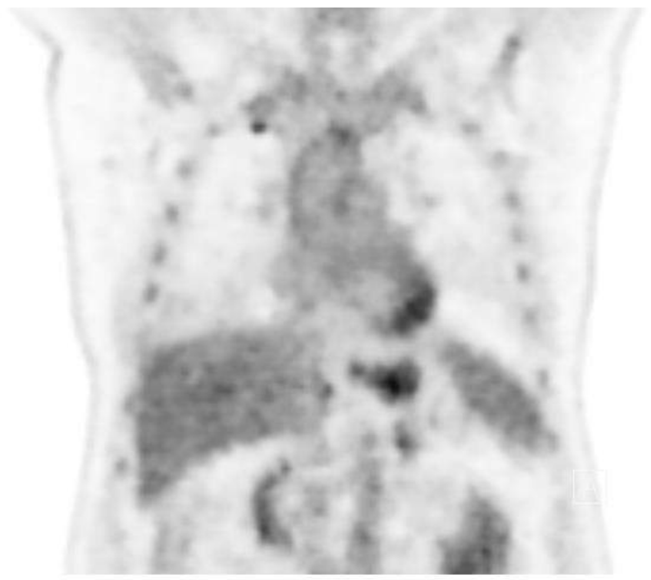
	Siemens	GE	Correction
Resolution / PSF modelling (recovery)	HD·PET	Sharp IR	Reconstruction
Time-of-flight	ultra-HD·PET (when with above)	VuePoint FX (VPFX)	Acquisition and reconstruction
Regularisation (penalisation)	Not available	Q.Clear (includes all above)	Reconstruction

All of the above provide improved image quality and noise reduction

Impact on image appearance : Q.Clear

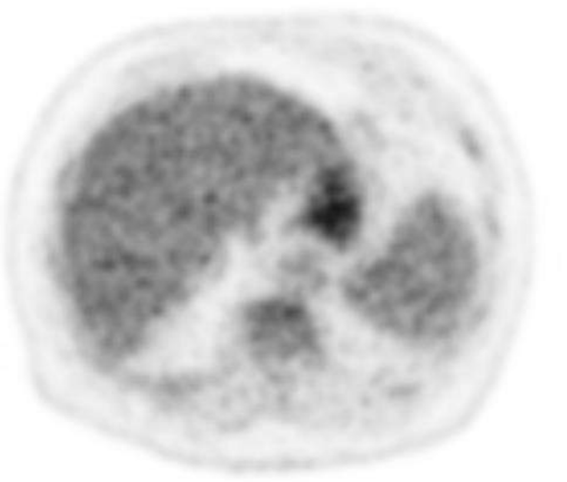
Liver
Mean : 2.88
SD : 0.21
SNR : 13.7

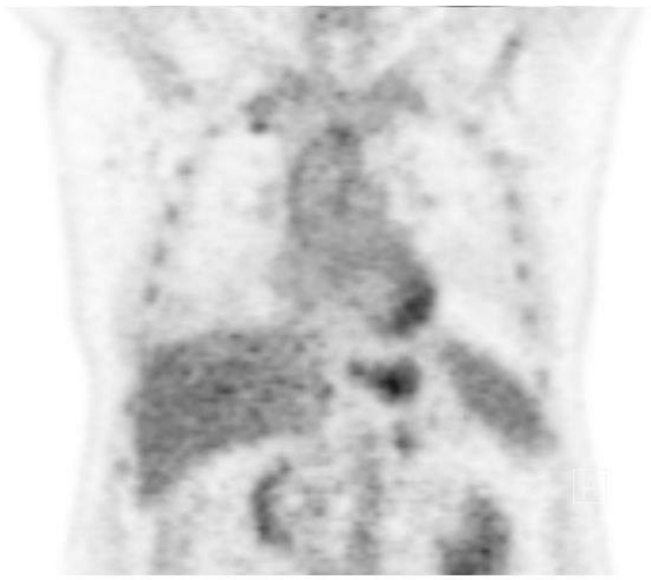




Q.Clear

Liver
Mean : 2.92
SD : 0.28
SNR : 10.4



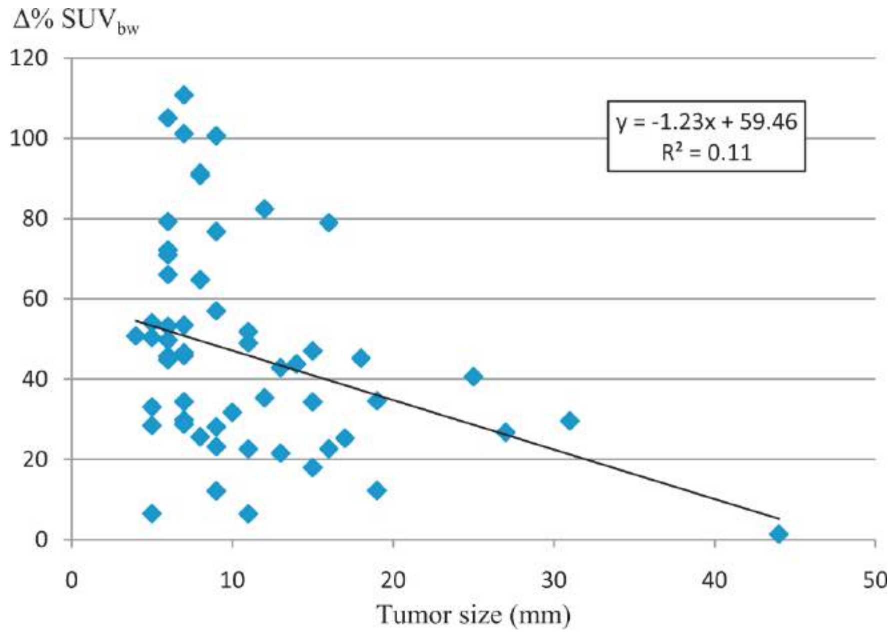


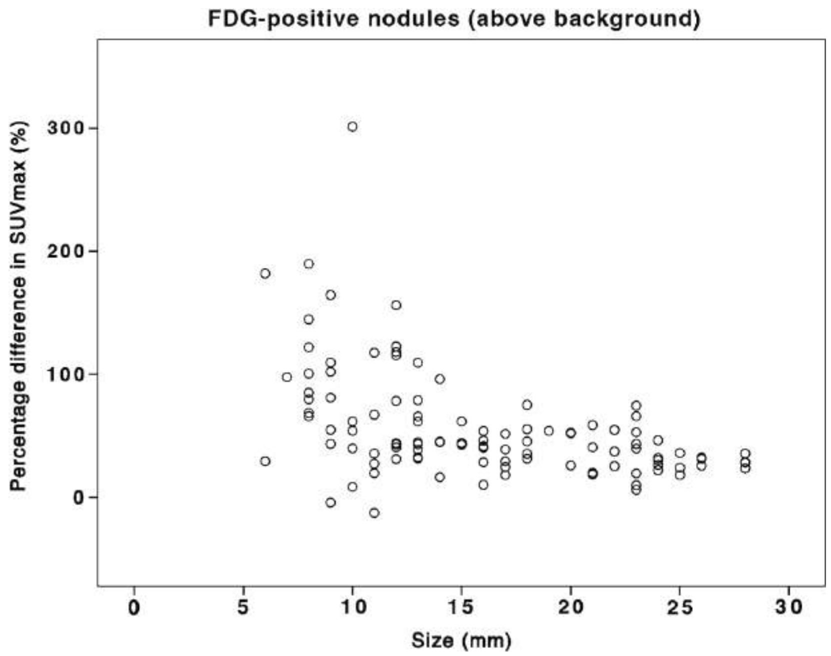
TOF

Data courtesy of Dan McGowan, Oxford University Hospitals

Impact on quantification

- These algorithms all improve signal to noise
- Therefore, if noise is fixed then signal increases
  - Signal increase = SUV increase
- Most prominent increase seen in smaller lesions





Andersen *et al*. *Eur J Radiol* 2013; **82**:862
Teoh *et al*. *Eur Radiol* 2016; **26**:576

Quantification with new technology

Table 5 Diagnostic performance of OSEM and BPL in detecting malignant nodules on the basis of semi-quantitative analysis using optimum SUV_{max} threshold (3.5 and 4.4, respectively) and visual analysis

	Semi-quantitative		Visual	
	OSEM	BPL	OSEM	BPL
All (*n*=121)				
Sensitivity	60.4 %	67.0 %	84.0 %	86.8 %
Specificity	73.3 %	66.7 %	33.3 %	20.0 %
Accuracy	62.0 %	67.0 %	77.7 %	78.5 %
≤10 mm (*n*=31)				
Sensitivity	44.4 %	55.6 %	100.0 %	100.0 %
Specificity	75.0 %	75.0 %	69.2 %	60.0 %
Accuracy	48.4 %	58.1 %	87.1 %	87.1 %
>10 mm (*n*=90)				
Sensitivity	65.8 %	70.9 %	89.9 %	89.9 %
Specificity	72.7 %	63.6 %	45.5 %	27.3 %
Accuracy	66.7 %	70.0 %	84.4 %	82.2 %

SUV_{max}: threshold

OSEM 3.5   Q.Clear 4.4

Table 5 Diagnostic performance of ordered subset expectation maximum (OSEM) and Bayesian penalised likelihood reconstruction (BPL) in detecting malignant nodes based on size, using optimum maximum standardised uptake value (SUV_{max}) threshold (3.0 and 4.0, respectively)

	Nodes > 10mm (n=24)		Nodes ≤ 10mm (n=88)	
	OSEM	BPL	OSEM	BPL
Sensitivity	100.0 %	100.0 %	28.6 %	21.4 %
Specificity	23.1 %	23.1 %	85.1 %	87.8 %
Accuracy	58.3 %	58.3 %	76.1 %	77.3 %

SUV_{max}: threshold

OSEM 3.0   Q.Clear 4.0

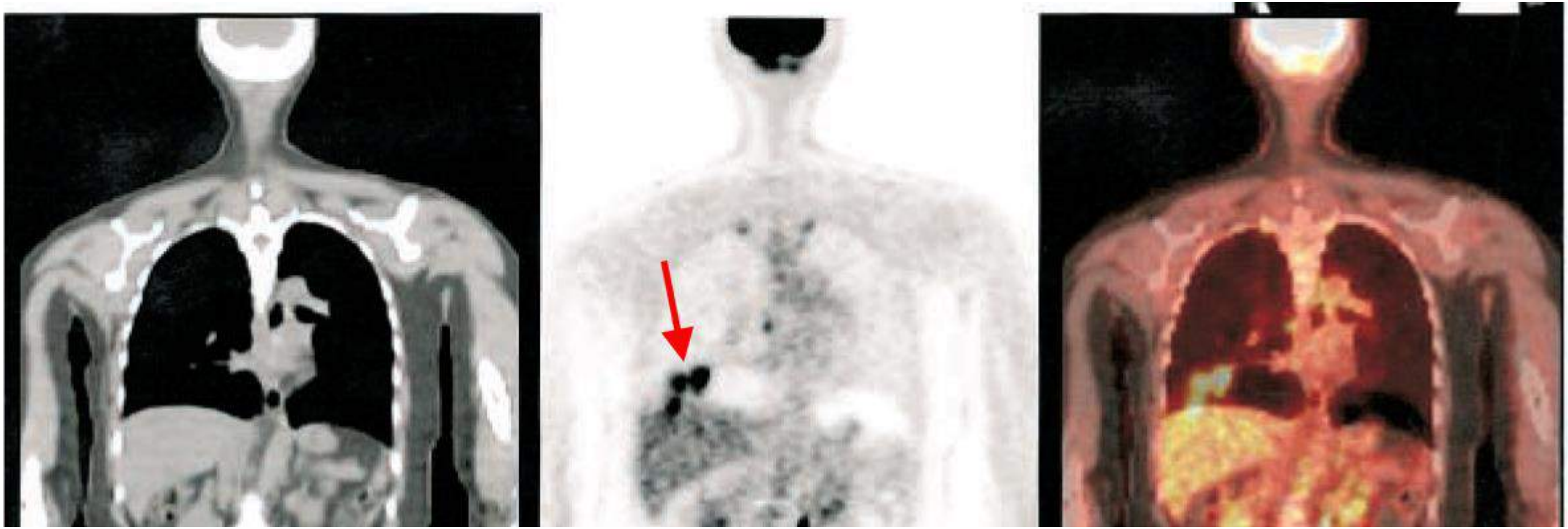
Teoh *et al*. *Eur Radiol* 2016; **26**:576
Teoh *et al*. *Eur Radiol* 2016; **26**:4098

Motion management

- As image quality improve the ever-present degrading factor of motion becomes an increasingly relevant challenge to address
- Quicker scans may reduce motion due to discomfort
- But the patient still breathes!
- Breath-hold PET?
  - Still challenging on "standard" FOV, even with SiPM
  - Probably achievable on LAFOV systems
  - Match to CT

Motion management

Incorrect localisation of lesions close to lung-liver boundary



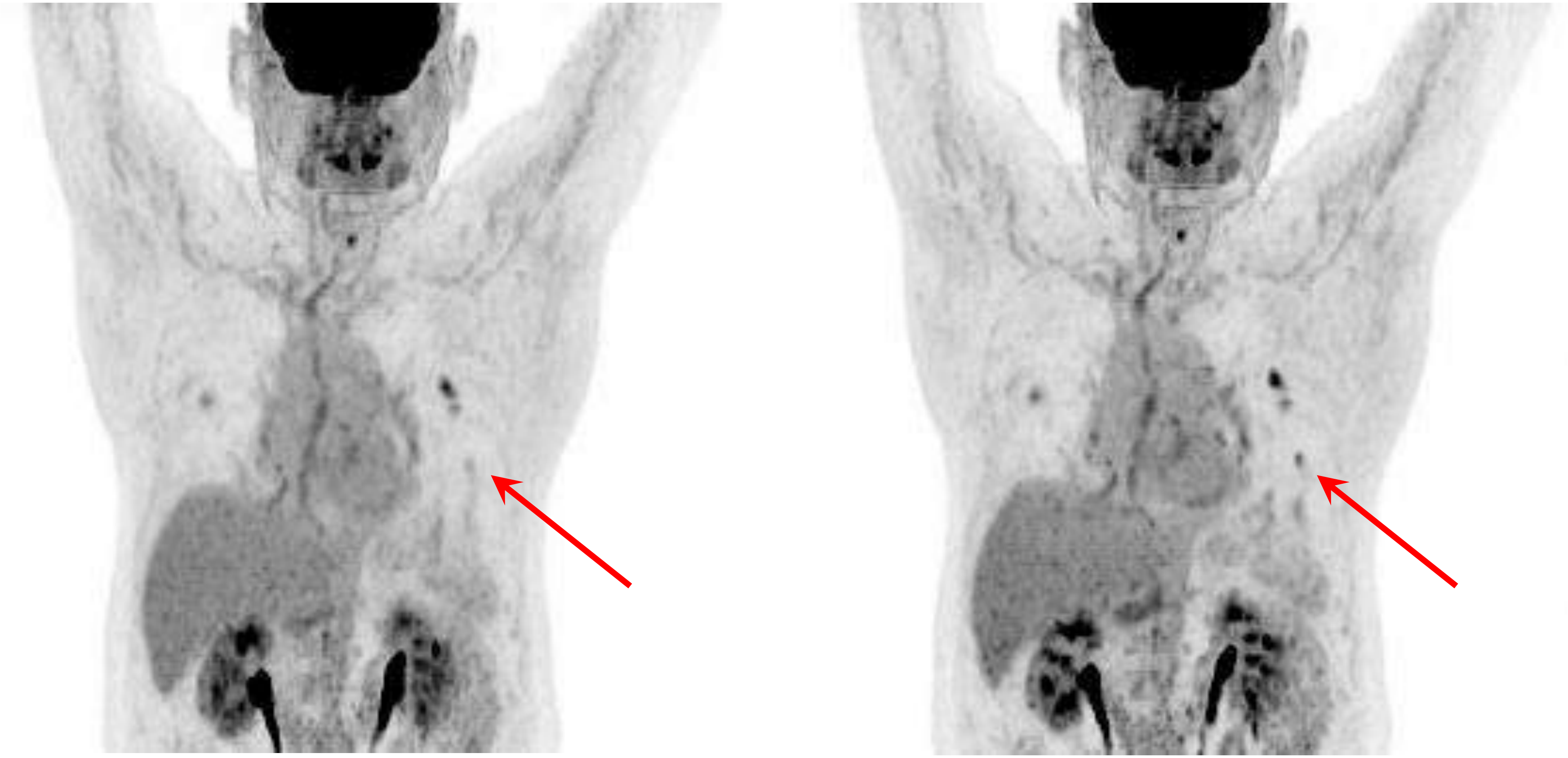
Current gated respiratory motion compensation discards image data

Images are noisier – have to scan for longer

Motion management

- "Current generation" motion measurement relies heavily on external monitoring systems
  - Increased set-up time
  - Not 100% robust
  - Assume external motion correlates with internal motion
- For something to be adopted into routine practice it needs to be
  - Accurate
  - Reliable
  - Easy
  - Affordable (or at least relatively!)
- Now have commercial PET data-driven gating (DDG)

Motion management



New motion algorithms are producing "motion-free" images without count loss

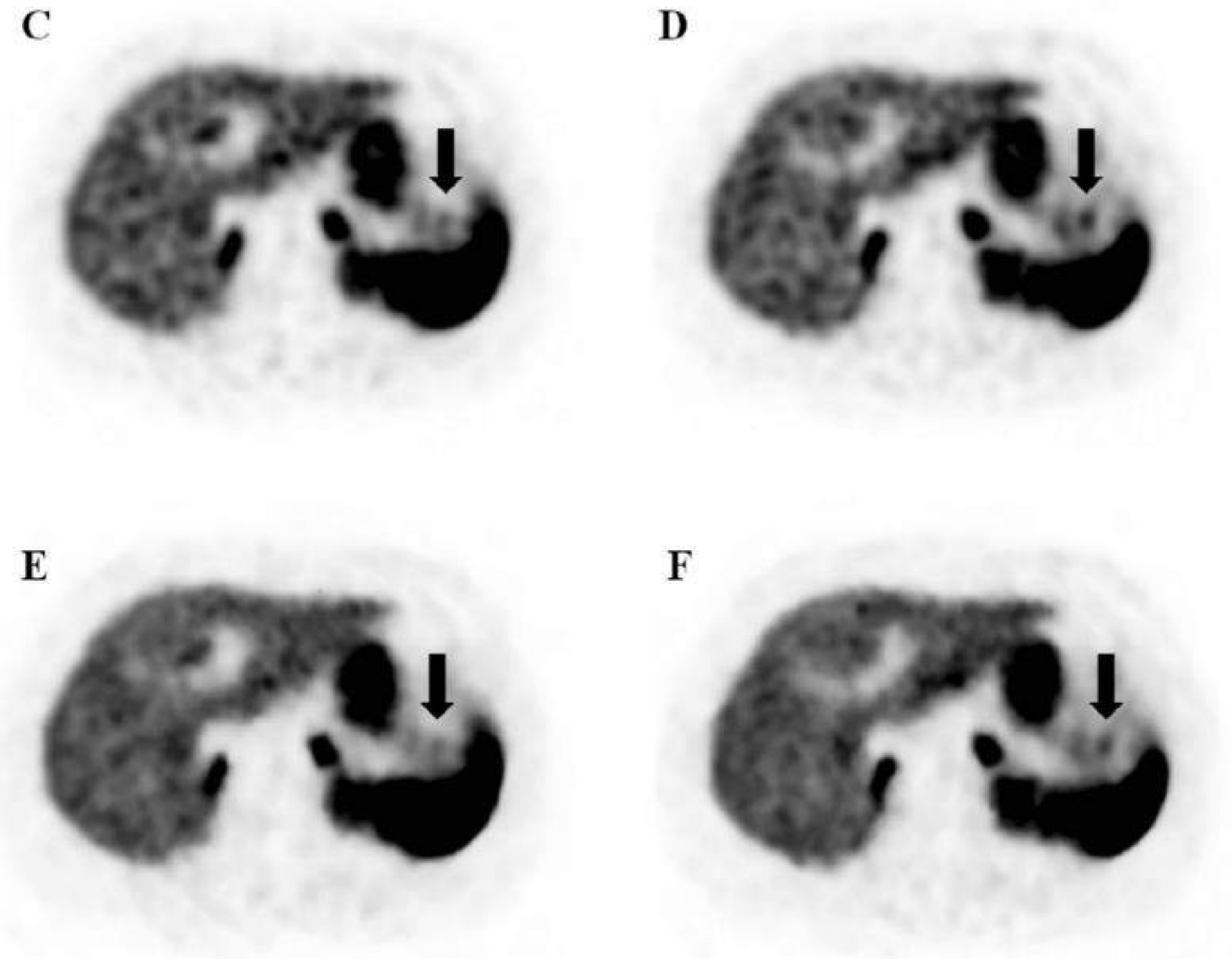
Motion management

OSEM

SUV_{max} 6.4

OSEM+DDG

SUV_{max} 8.6



Q.Clear

SUV_{max} 6.2

Q.Clear+DDG

SUV_{max} 7.6

Liberini *et al*. *Nature Sci Rep*. 2021; **11**:2273

What does the future hold?

- Economy of scale for increased axial FOV
  - “Affordable” system with 40 to 50 cm AFOV?
- Improvements to TOF
  - 100 ps in the next 10 years
  - New crystal developments
  - New detector design
- Adoption of DDG / motion correction
- Utilisation of AI / machine learning
  - More automation
  - Improvements to image reconstruction
  - Better noise characteristics

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Transition from Biograph mCT to Vision

System comparison

	Biograph mCT Flow	Biograph Vision 600
Detector technology	PMT	SiPM
Crystal size	4.0 mm × 4.0 mm	3.2 mm × 3.2 mm
Axial field of view	22.1 cm	26.3 cm
TOF performance	540 ps	214 ps
Sensitivity	9.7	16.0
Effective sensitivity*	**19.1**	**79.1**

* For 25 cm uniform object, correcting for Gaussian TOF profile

Our department's main limiting factor

Protocol

Patient size	CBM (torso)	Typical vertex – thigh scan time
< 85 kg and BMI < 28	2.2 mm / s	7 – 8 min
85 kg to 115 kg or BMI > 28	1.7 mm / s	9 – 10 min
> 115 kg or BMI > 34	1.3 mm / s	12 – 14 min
> 115 kg or BMI > 34	1.0 mm / s	16 – 18 min

Speed up over head (high uptake and low attenuation)

3.5 MBq / kg up to 280 MBq at 80 kg

Fixed 280 MBq above and adjust bed speed

Utilising continuous bed motion (FlowMotion)

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Benefits of SiPM systems : imaging times at MFT

- Biograph Vision FDG vertex to mid-thigh (CBM acquisition)
  - Median scan time: 8:44
  - Inter-quartile range: 7:46 to 9:55

- Biograph mCT FDG vertex to mid-thigh (Step & shoot acquisition)
  - Median scan time: 16:00
  - Inter-quartile range: 14:00 to 17:30

- No scans exceed 20 minutes (including wholebody)
- BUT: we did not change our administered activity!

Image quality : liver SNR on Biograph mCT

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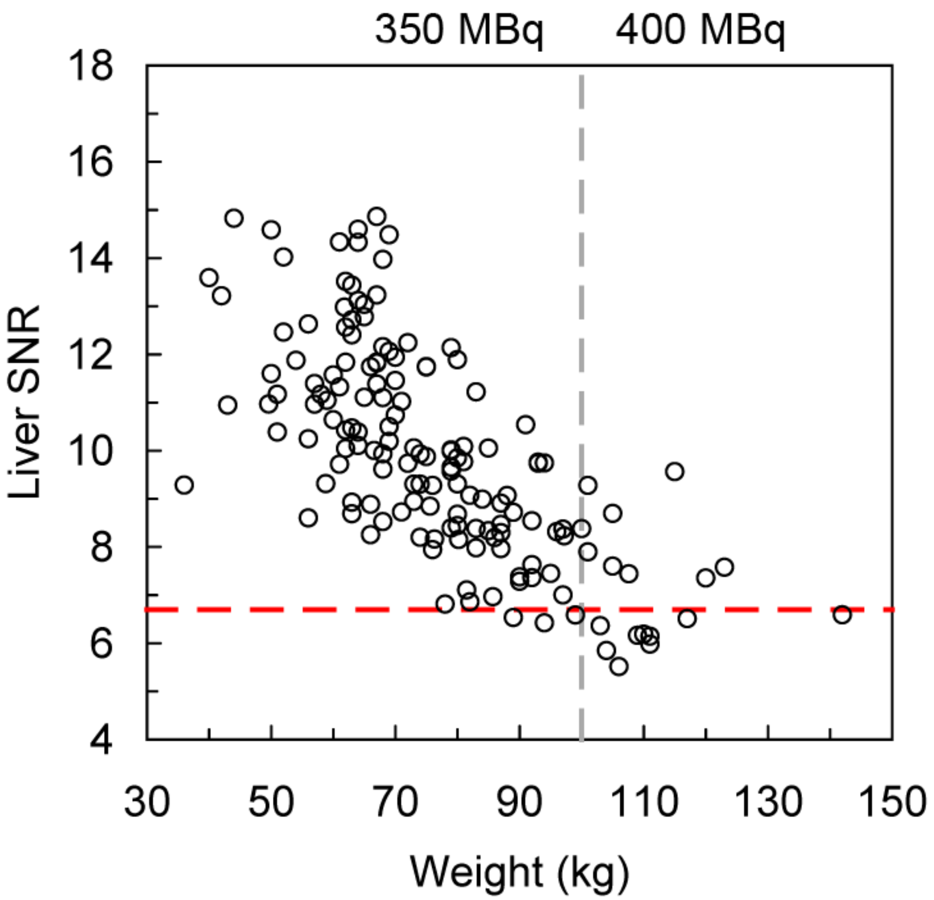
2009 – 2014 non-TOF



2014 TOF (semi weight-based)

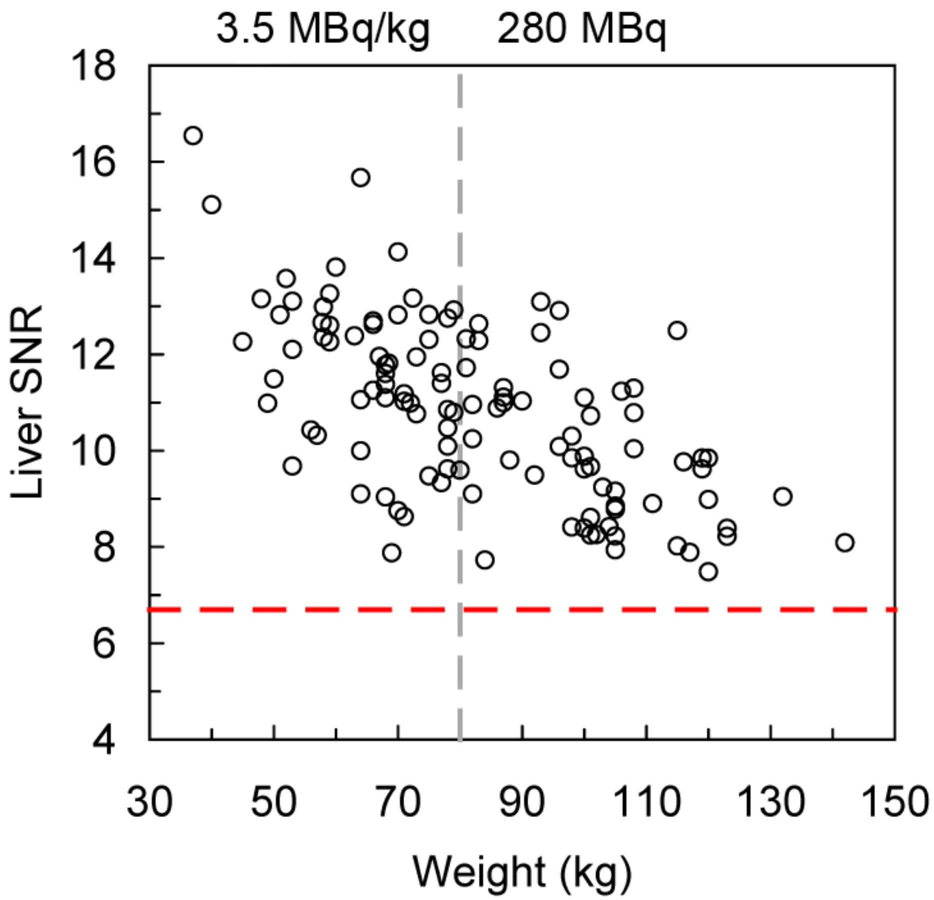
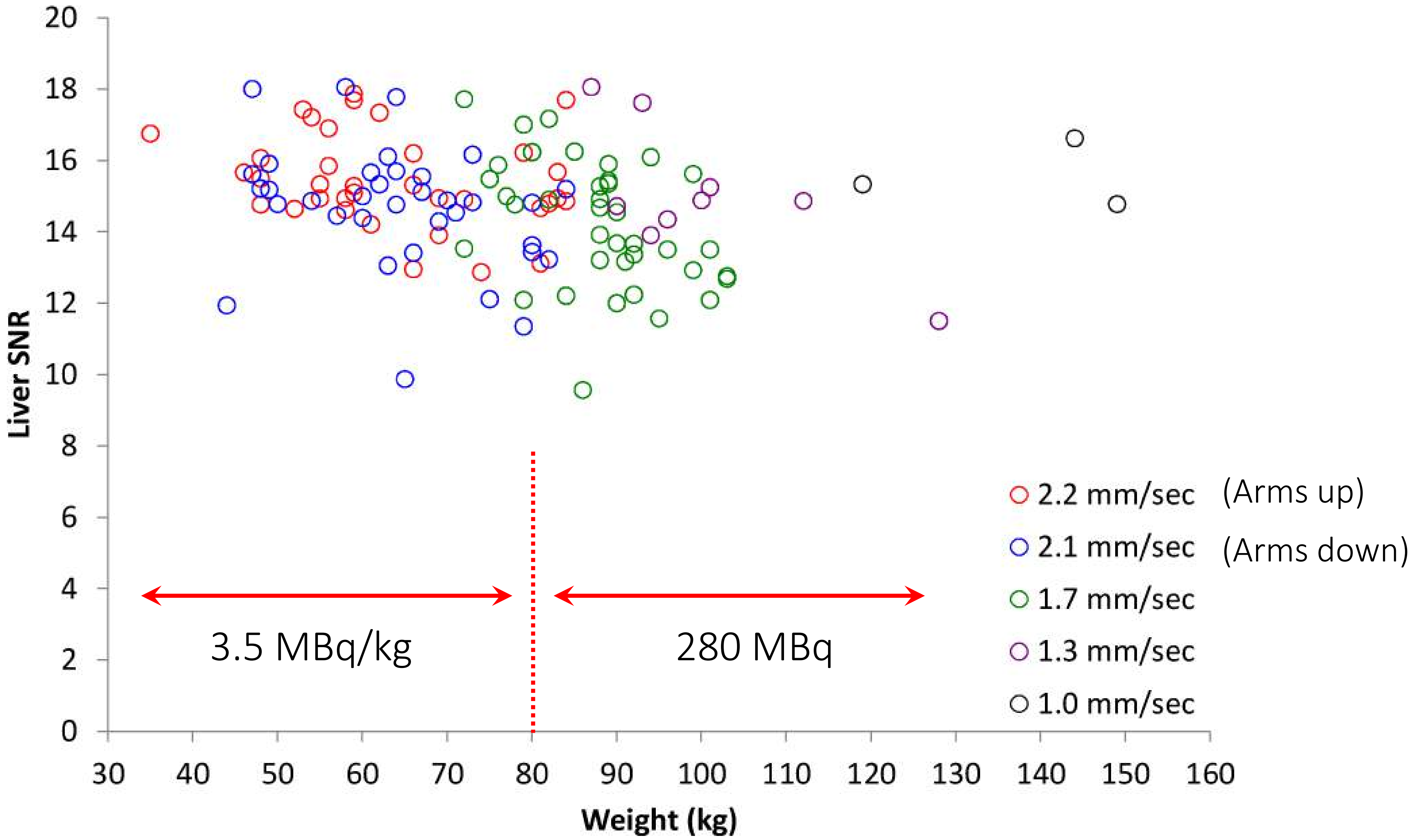


Image quality : Biograph Vision



SUV_{max} recovery : how it started, how's it going

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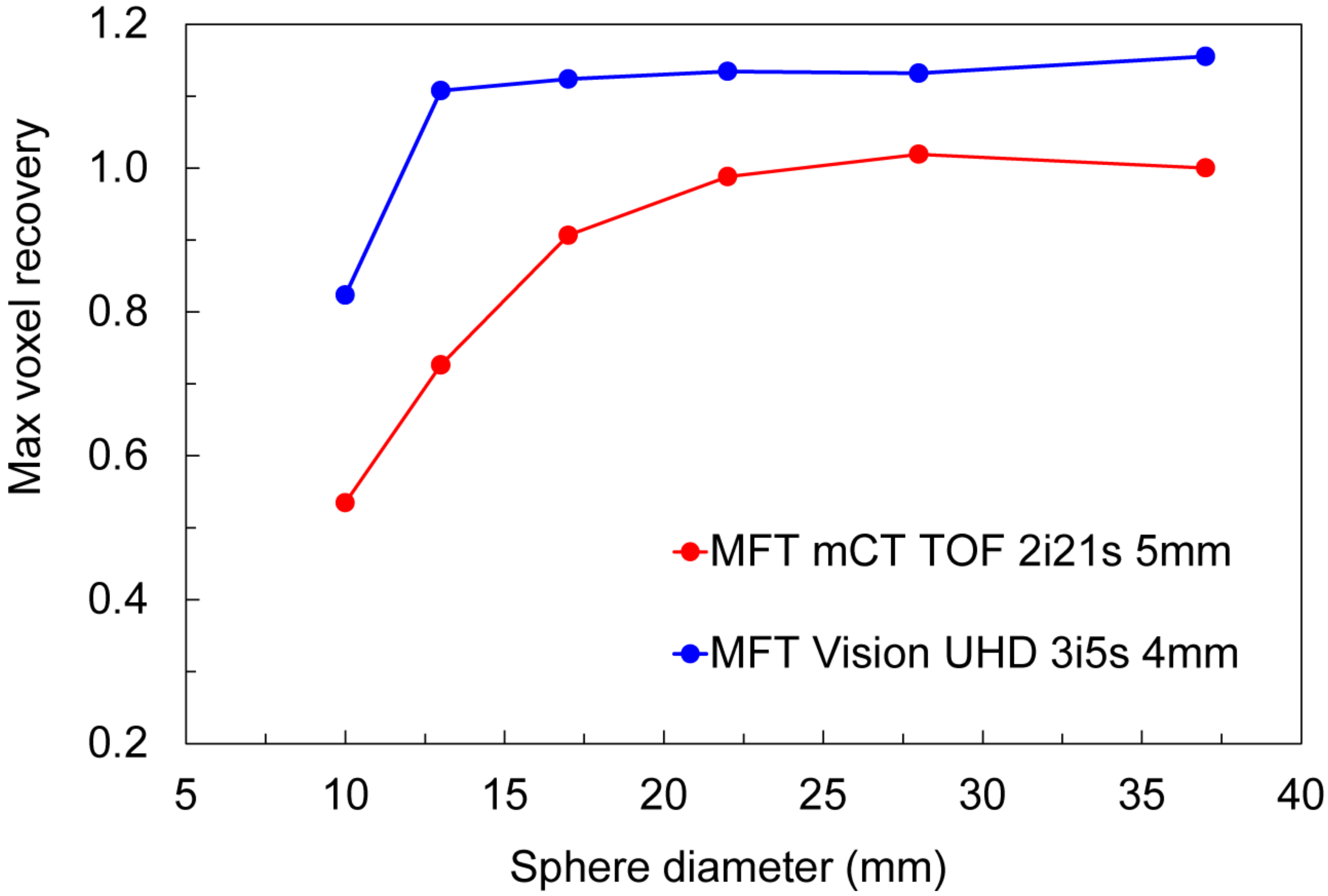

Summary

- No change to administered activity
  - Largely based on manually dispensing
- Decreased scan time
  - Now scanning in approximately half time
- Improved image quality
  - Increased and more consistent image quality
  - Increased visualisation and SUV_{max}

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Thanks for listening

ian.armstrong@mft.nhs.uk

Out with the old
In with the new

Dr Glen Gardner
Clinical Research Centre
Ninewells Hospital
Dundee

PET Reconstruction Times (Typical)	HD•PET*	ultraHD•PET*
Reconstruction time per bed[1] (200x200 matrix, 81 imaging planes)	25 sec	25 sec
Reconstruction time per bed with TrueV[1] (200x200 matrix, 109 imaging planes)	30 sec	35 sec
PET NEMA 2012 Performance (Typical)		
Scatter fraction at Peak NECR	37%	
Scatter fraction (low activity conc.)	33%	
Count rate accuracy (Δr mean bias ≤22 kBq/cc)	+/-4%	
Count rate accuracy (Δr mean bias @ peak NEC)	+/-4%	
Spatial Resolution – Axial (Typical)	**Standard Processing (256x256)**	**HI-REZ Processing (400x400)**
FWHM @ 1 cm (mm)	5.7	4.7
FWHM @ 10 cm (mm)	6.2	6.1
Spatial Resolution – Transverse (Typical)	**Standard Processing (256x256)**	**HI-REZ Processing (400x400)**
FWHM @ 1 cm (mm)	6.0	4.5
FWHM @ 10 cm (mm)	6.3	5.2
	Standard	**TrueV***
Sensitivity (cps/kBq)	5.8	10.2
Peak NEC rate (kcps)	107 @ ≤30 kBq/cc	180 @ ≤28 kBq/cc
Peak trues rate (kcps)	380 @ ≤46 kBq/cc	610 @ ≤40 kBq/cc

NEMA performance measures represent average values derived from internal testing. All measurements are performed with the factory LLD setting of 435 keV.

Discovery MI Fully Digital PETCT
Lightburst Digital Detector

Light Shield

Scintillator (LBS) crystal array **with light guides** and Enhanced Spectral Reflectors (ESR)

Silicon Photomultiplier (SiPM) with electronics (ASICS) designed for Digital Compton Recovery

LightBurst Digital Detector	
Sensitivity[††]	13.5 cps/kBq
Timing Resolution	385 psec
Sensitivity/mm[††]	0.068 cps/kBq*mm
Scatter fraction[††]	41%
Clinical NECR[††]	53 kcps @ 2.4 kBq/ml
Peak NECR[††]	180 kcps @ 20 kBq/ml
Coincidence window	4.9 ns
Energy threshold	425 KeV

LightBurst Digital Detector	
Scintillator material	LBS-Lutetium based scintillator
Scintillator dimensions	3.95 mm x 5.3 mm x 25 mm
Number of detector rings	36 (19,584 total crystals)
SiPM Channels	9,792 (1,632 Hex-Anode SiPMs)
Number of detectors	544 blocks
Axial field of view	20 cm
Transaxial field of view	70 cm
Slice overlap	User defined 1-35

Resolution	VUE Point HD[7]
Axial @ 1 cm	4.8 mm
Axial @ 10 cm	4.7 mm
Transaxial @ 1 cm	4.0 mm
Transaxial @ 10 cm	4.5 mm

imagination at work

Discovery MI Fully Digital PETCT
Lightburst Digital Detector

Light Shield

Scintillator (LBS) crystal array **with light guides** and Enhanced Spectral Reflectors (ESR)

Silicon Photomultiplier (SiPM) with electronics (ASICS) designed for Digital Compton Recovery

LightBurst Digital Detector	
Sensitivity††	13.5 cps/kBq
Timing Resolution	385 psec
Sensitivity/mm††	0.068 cps/kBq*mm
Scatter fraction††	41%
Clinical NECR††	53 kcps @ 2.4 kBq/ml
Peak NECR††	180 kcps @ 20 kBq/ml
Coincidence window	4.9 ns
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LightBurst Digital Detector	
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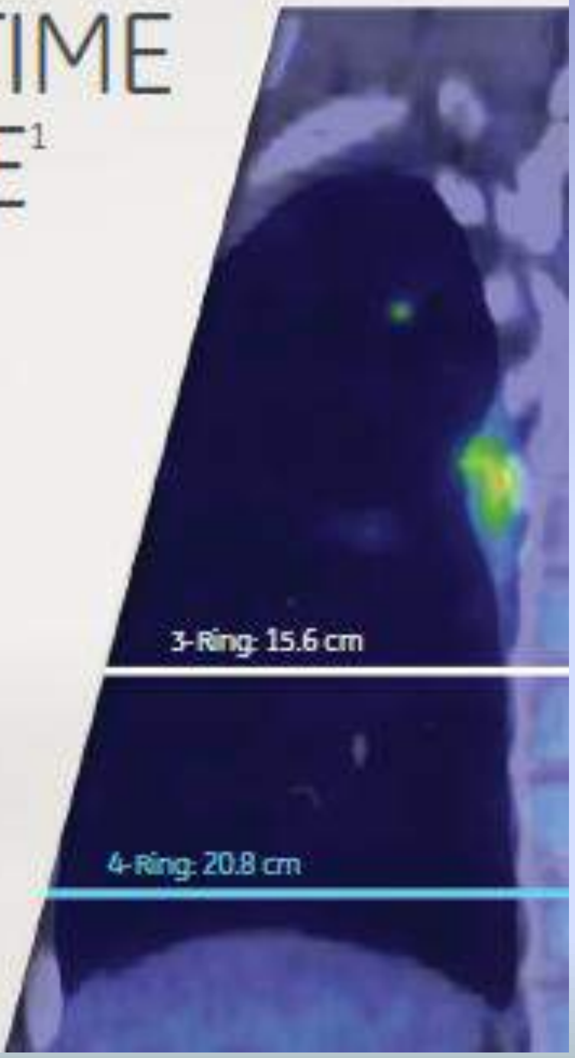
Resolution	VUE Point HD[7]
Axial @ 1 cm	4.8 mm
Axial @ 10 cm	4.7 mm
Transaxial @ 1 cm	4.0 mm
Transaxial @ 10 cm	4.5 mm

imagination at work

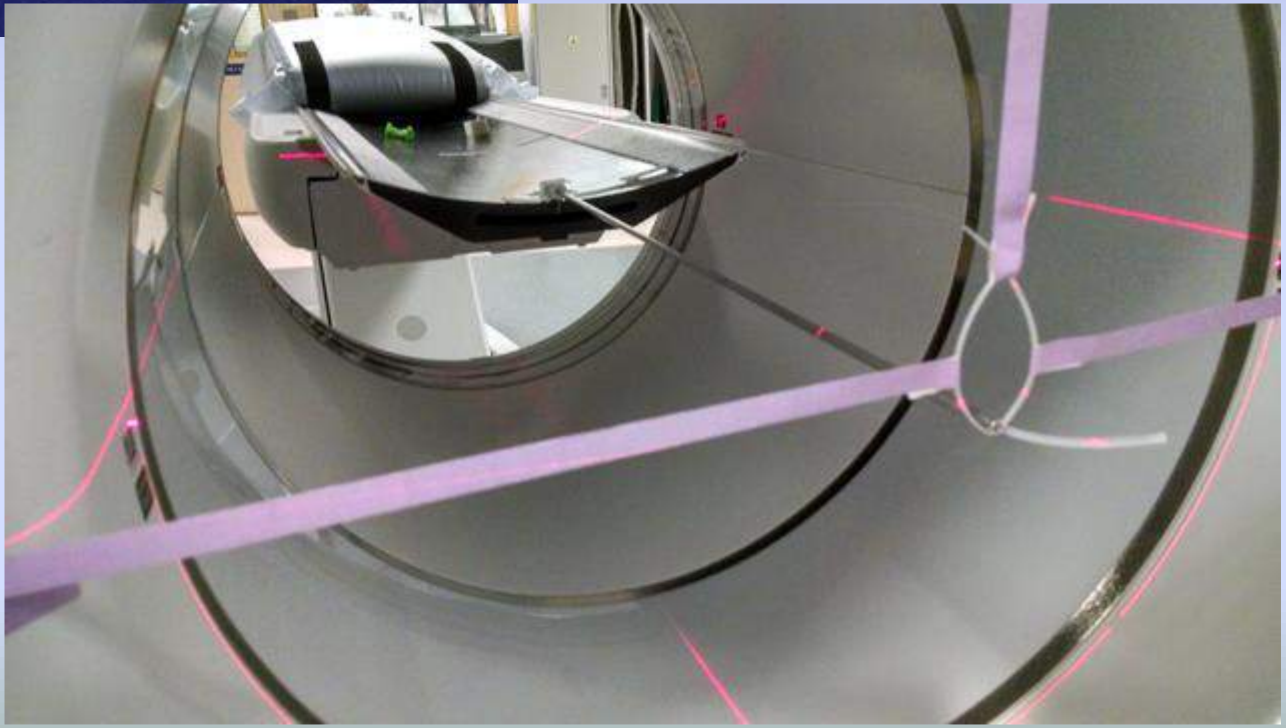
SCAN IN ½ THE TIME AND ½ THE DOSE[1]

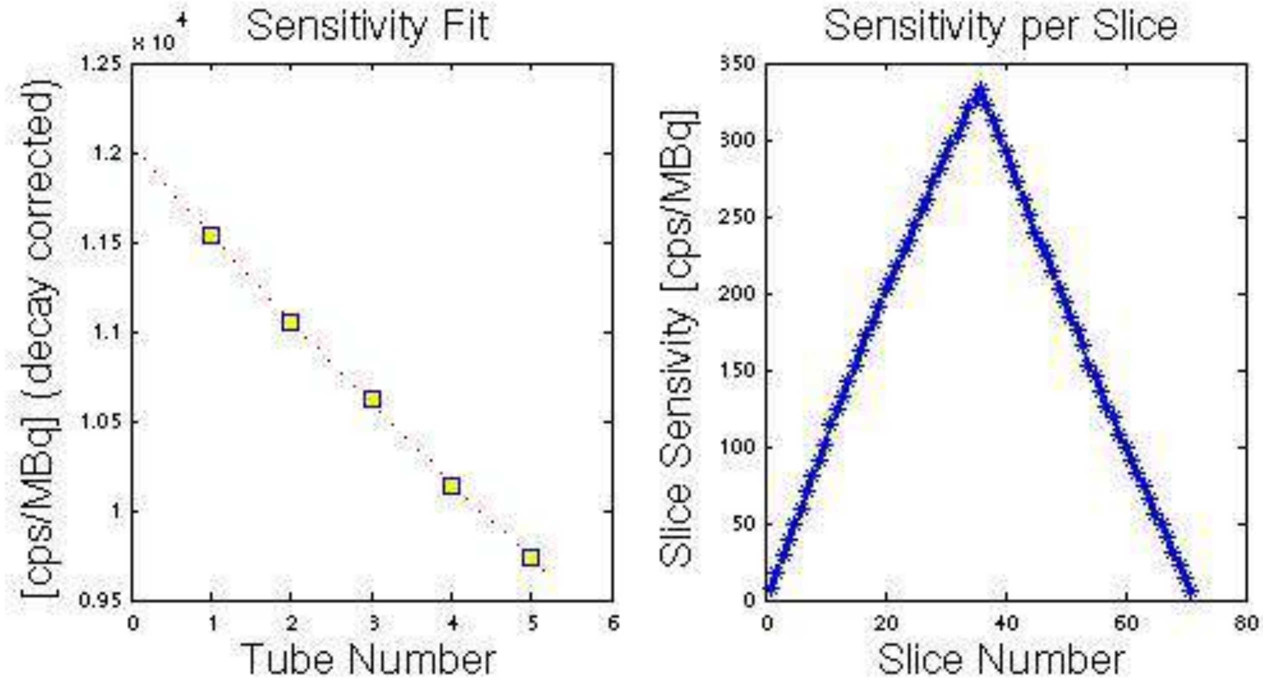
The LightBurst PET detector does more than increase the clarity of the image; it increases the speed that you acquire it, helps to reduce the dose you expose your patient to and aids in strengthening your confidence to see smaller lesions. It's technology that was designed with a goal towards personalizing care. We focused on the variables that directly affect clinical outcomes to develop technologies that really make a difference, an innovative PET detector that cuts scan times and dose amounts in half.

A BRIGHTER WAY TO IMAGE



sinogram alignment (visual inspection)to check positioning of the line in prior measurements.





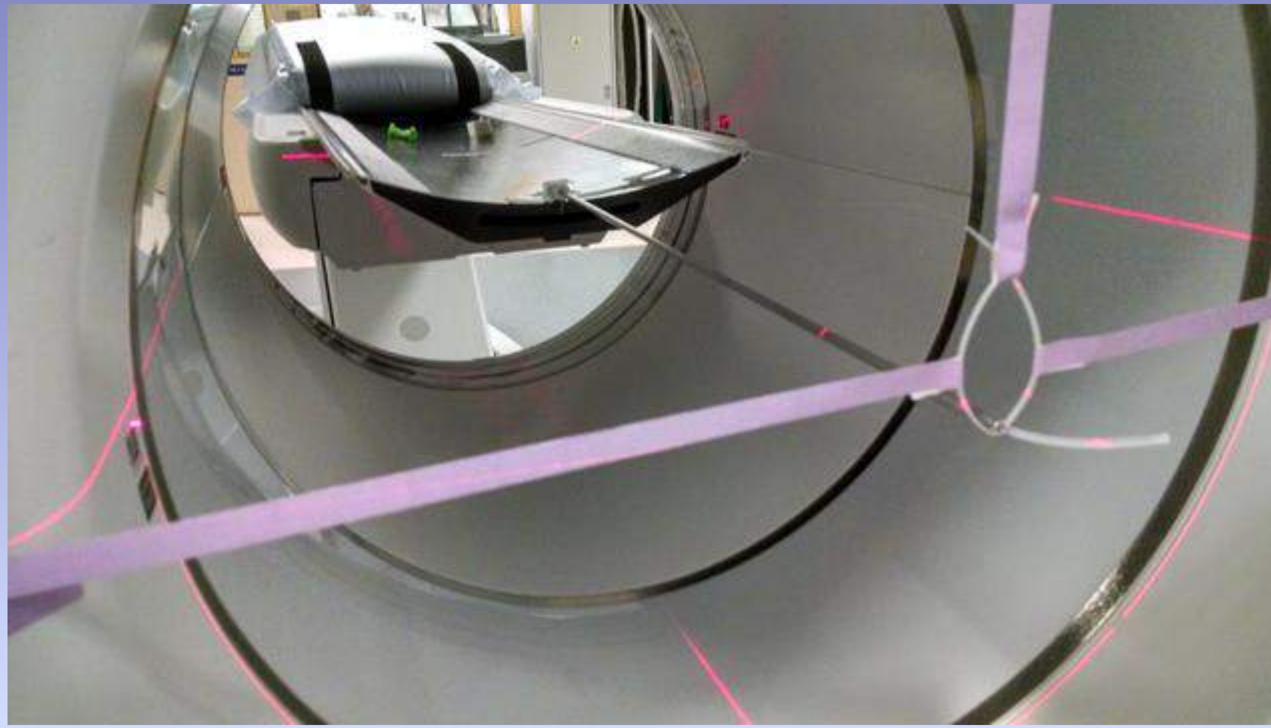
Sensitivity: 12.046 [cps/kBq]
Attenuation: 2.133e-02 [1/mm]
Half Life: 6586.2002 [s]
Fit Type: 5 Point

Study:
Series: Frame 1
Acquired: 03-May-2017 14:46:39
Printed: 09-May-2017 12:57:39

Measurement cps/kBq	Scan Time	Centre	10cm offset
Manufacturers Specification	**NEMA protocol**	**12.60**	**11.88**
	BNMS response	**13.5**	**13.5**
Measured results			
19 April	15:35	12.48	
	15:53	11.43	
	16:07	12.21	
	16:29		12.75
24 April	13:41	12.22	
	13:56		12.72
	14:09	12.24	
	16:46	12.28	
	17:13		12.52
	17:32	12.69	
3 May	14:46	12.05	
	15:06	11.75	
	15:43	11.85	
4 May	15:37	12.11	
	16:06	11.87	
	16:19		12.16
	16:31		12.37
	16:31		12.37

- 2015 NIST standard for F-18
- 4% difference to old standard
- In 2015 the National Institute of Standards and Technology (NIST) published an article in the Journal of Nuclear Medicine revising the activity standard for the positron emitter F-18. They reported a change of -4% in its radioactivity standard for F-18.

- NIST standard 2008 -Cessna, J.T., *et al. "Radionuclide calibrator measurements of 18F in a 3-ml plastic syringe." Applied Radiation and Isotopes 66.6 (2008):988-993).*



```
<><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><<

<><><>  MOVE PHANTOM AS FOLLOWS TO ALIGN IT TO CENTER AXIS OF THE SCANNER ...
<><><> Looking from the front of the gantry:
<><><>   raise this end of the phantom by 0.99 mm along the Vertical direction
<><><>   move this end of the phantom by 0.66 mm to the right along the
horizontal direction
<><><> Looking from the back of the gantry:
<><><>   phantom does not need vertical adjustment from the back of gantry
<><><>   move this end of the phantom by 0.16 mm to the right along the
horizontal direction

<><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><><<
```

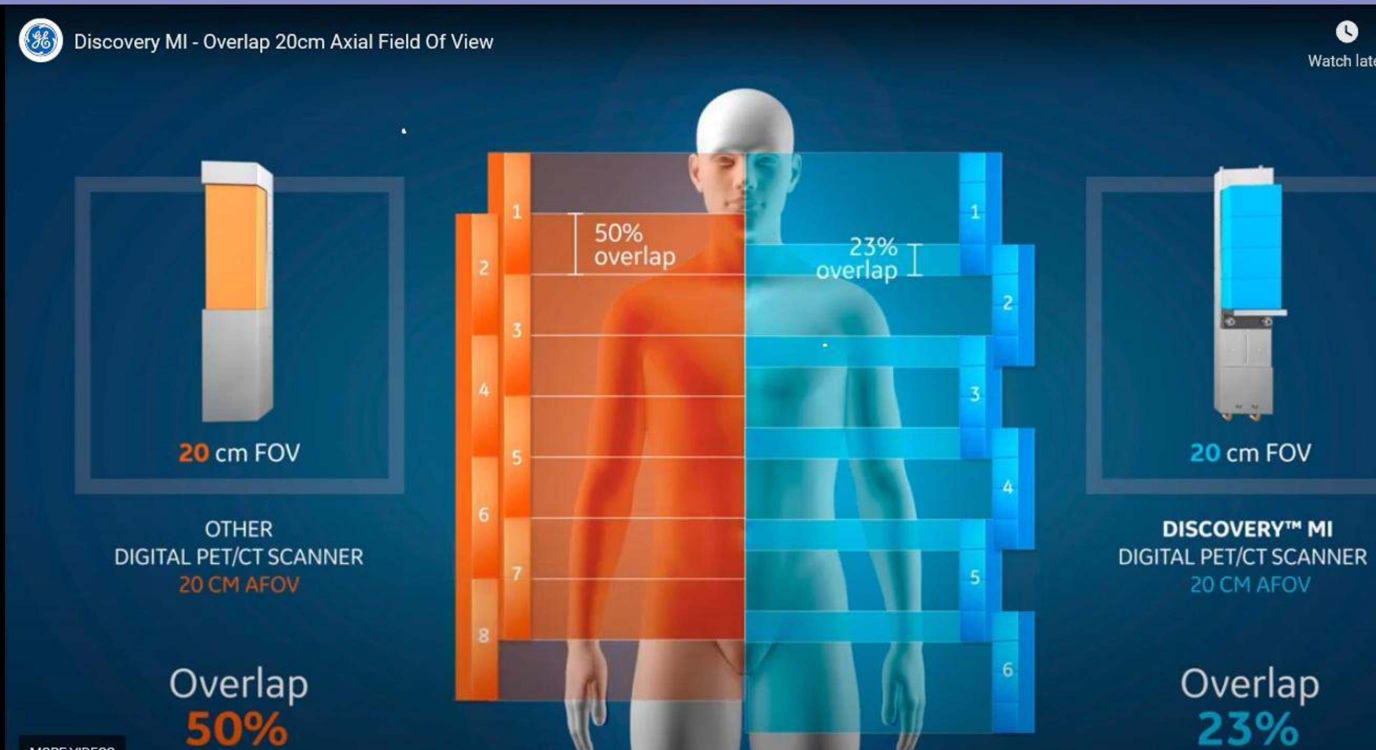
NHS Tayside

Summary of Results & Conclusions

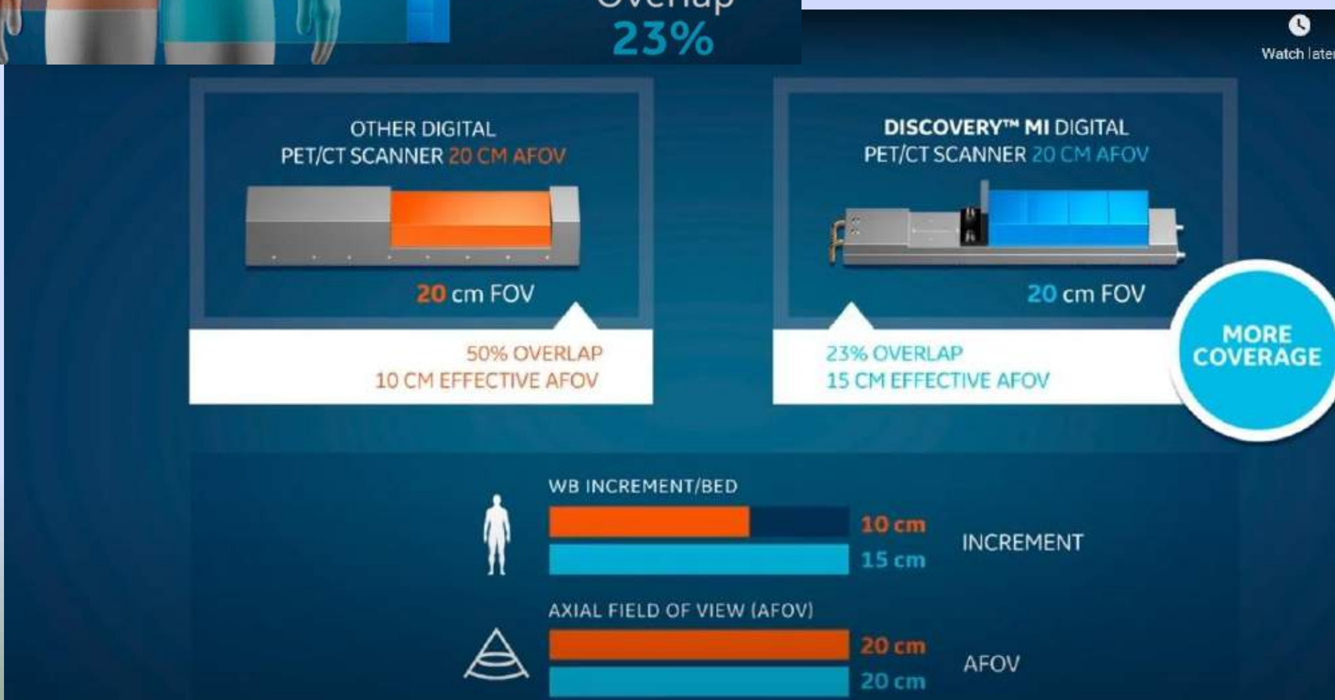
Sensitivity (cps/kBq)	Measured at Center per NIST 2015	Measured at 10 cm per NIST 2015	Center (4%) adjusted per NIST 2008	@ 10cm (4%) adjusted per NIST 2008)	Average center and 10cm per 2008
LSL (guarantee)			12.6	11.88	
Typical (datasheet)					13.5
GEHC phantom (official)	12.89	12.607	13.41	13.11	13.26
Ninewells phantom	12.584	12.414	13.09	12.91	13.0
AVERAGE (NHS – GE)	12.737	12.511	13.25	13.01	13.13

- The sensitivity of the Ninewells scanner is 13.13 cps/kBq.
  - This value is above the guaranteed Lower Spec Limit (LSL_{center} =12.6 cps/kBq) but it is below the typical value in data sheet (13.5 cps/kBq). There is no guarantee where a scanner will perform relative to typical spec. It can be on either side of the typical value.

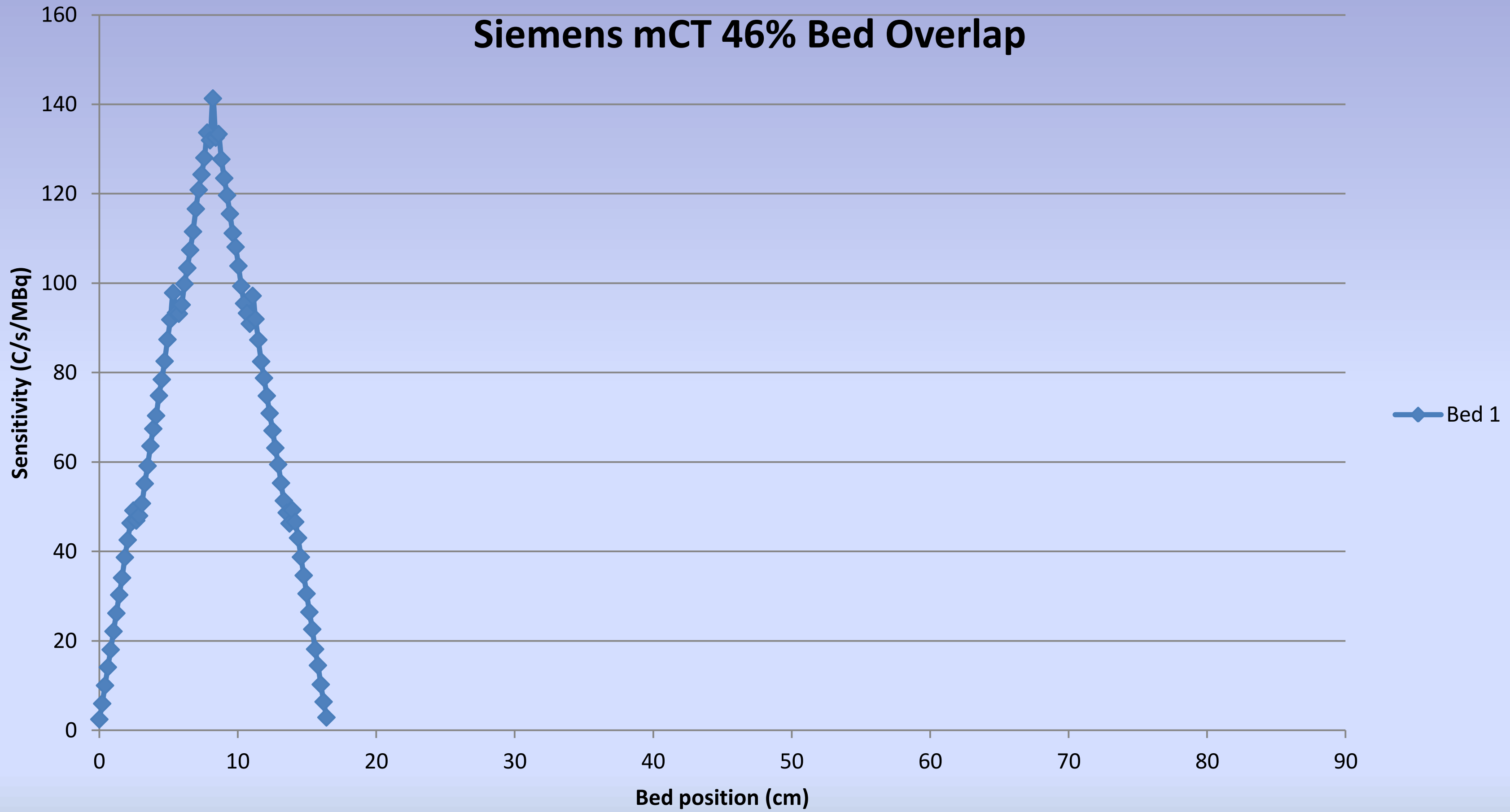
NHS Tayside

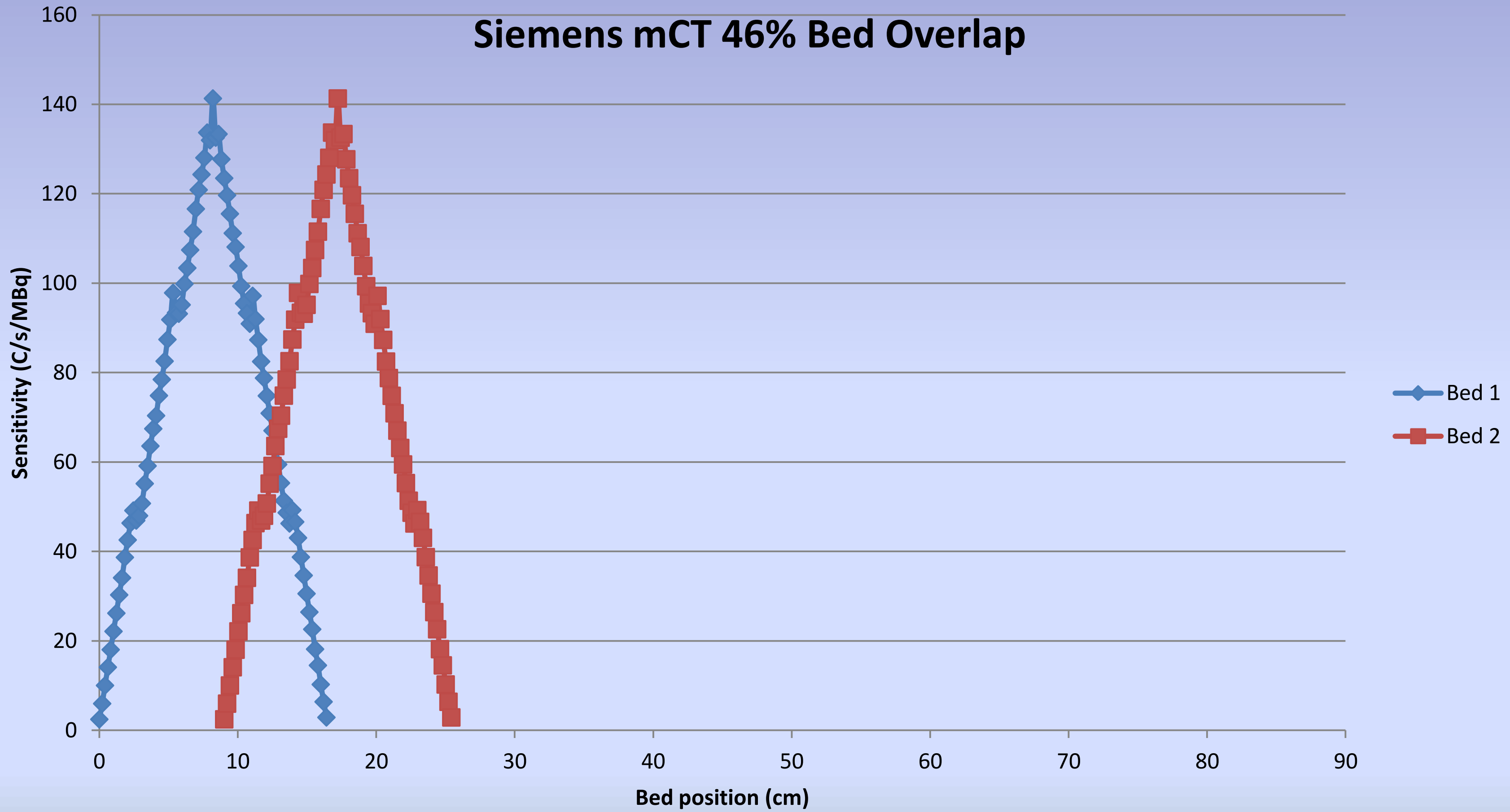


Discovery MI - Overlap 20cm Axial Field Of View
Watch later
50% overlap
23% overlap
20 cm FOV
OTHER
DIGITAL PET/CT SCANNER
20 CM AFOV
Overlap
50%
20 cm FOV
DISCOVERY™ MI
DIGITAL PET/CT SCANNER
20 CM AFOV
Overlap
23%
MORE VIDEOS

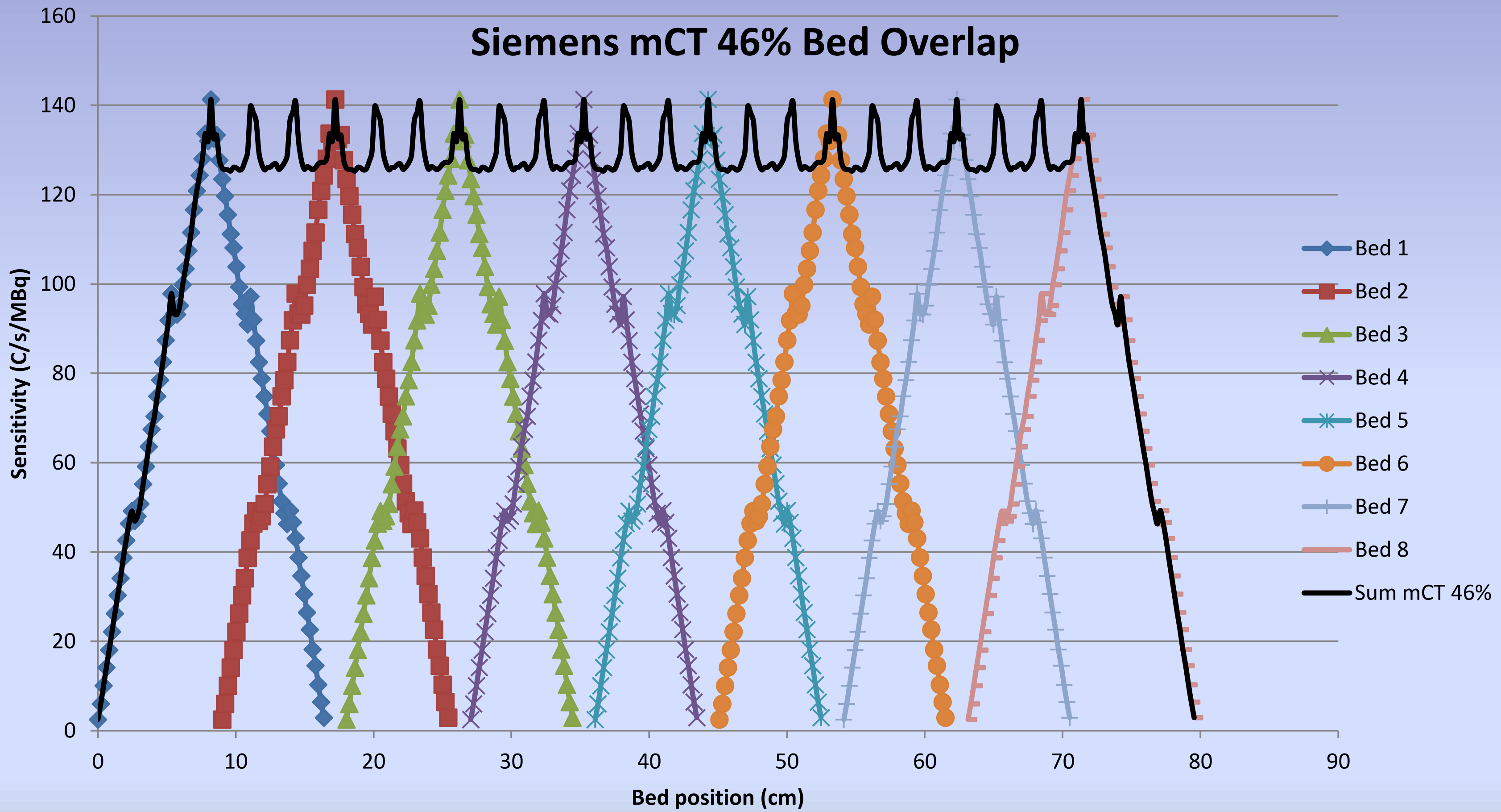


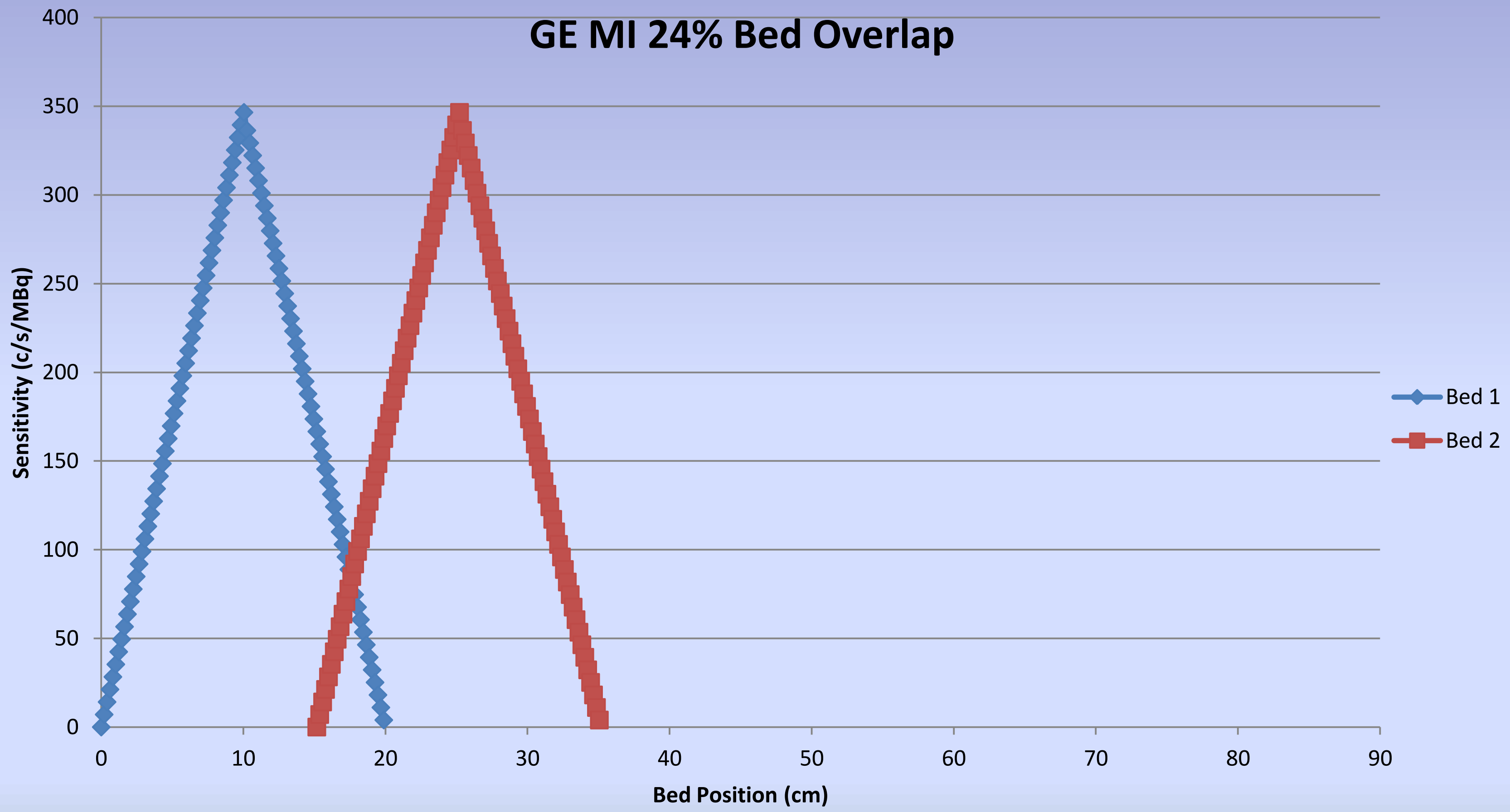
Watch later
OTHER DIGITAL
PET/CT SCANNER 20 CM AFOV
20 cm FOV
50% OVERLAP
10 CM EFFECTIVE AFOV
DISCOVERY™ MI DIGITAL
PET/CT SCANNER 20 CM AFOV
20 cm FOV
23% OVERLAP
15 CM EFFECTIVE AFOV
MORE COVERAGE
WB INCREMENT/BED
10 cm
15 cm
INCREMENT
AXIAL FIELD OF VIEW (AFOV)
20 cm
20 cm
AFOV

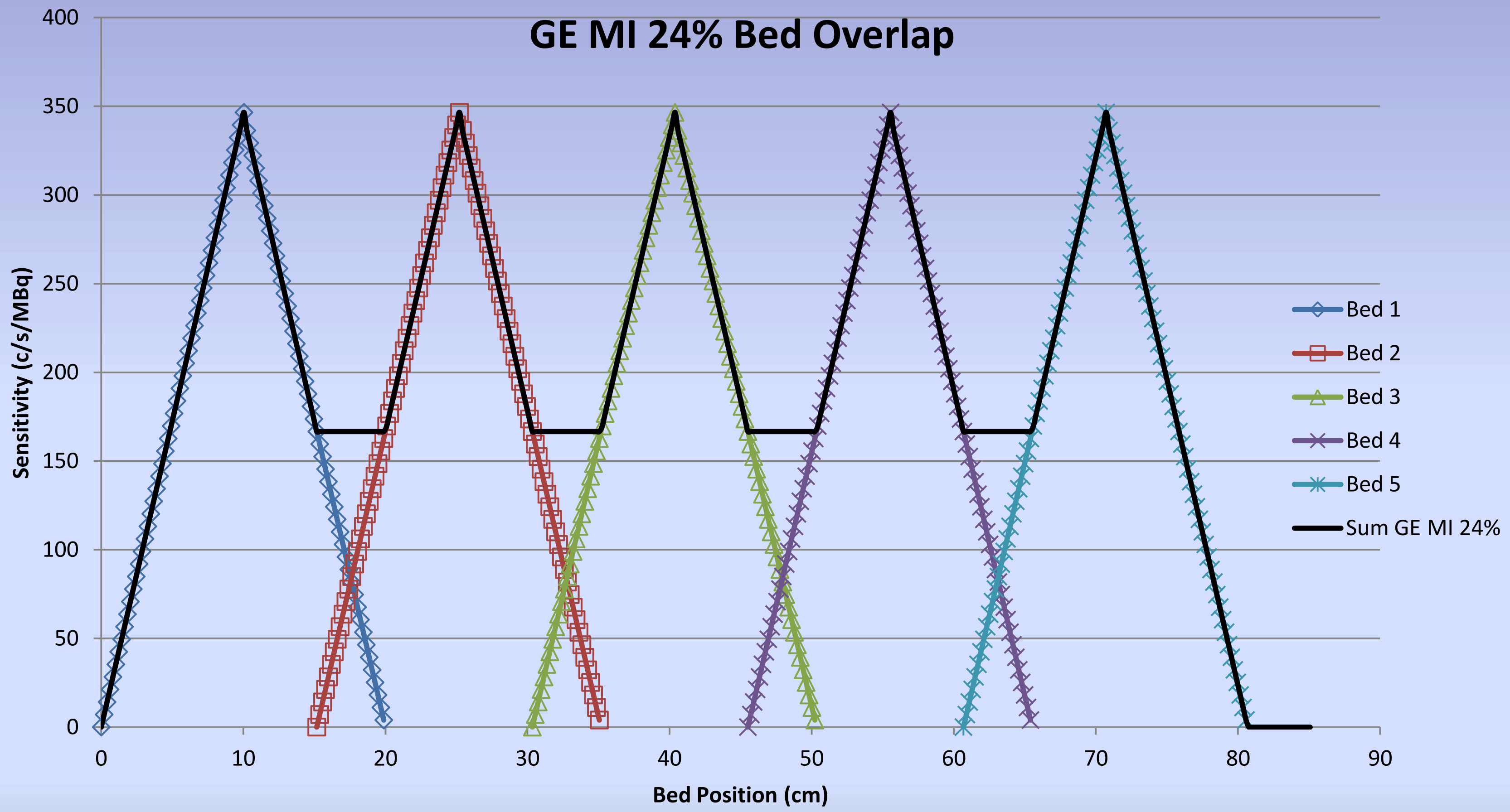

Siemens mCT 46% Bed Overlap
Sensitivity (C/s/MBq)
0
20
40
60
80
100
120
140
160
Bed position (cm)
0
10
20
30
40
50
60
70
80
90
Bed 1

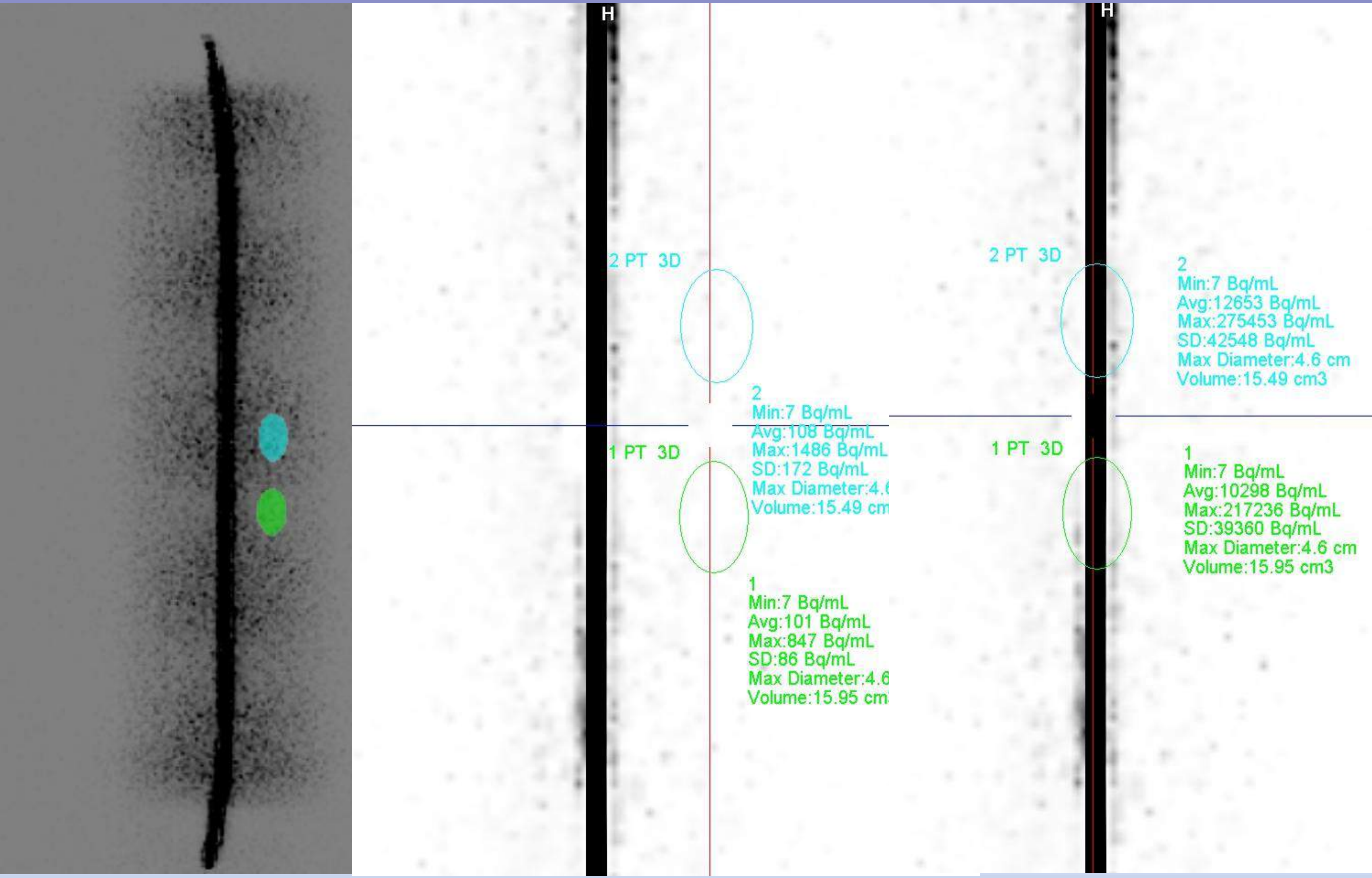


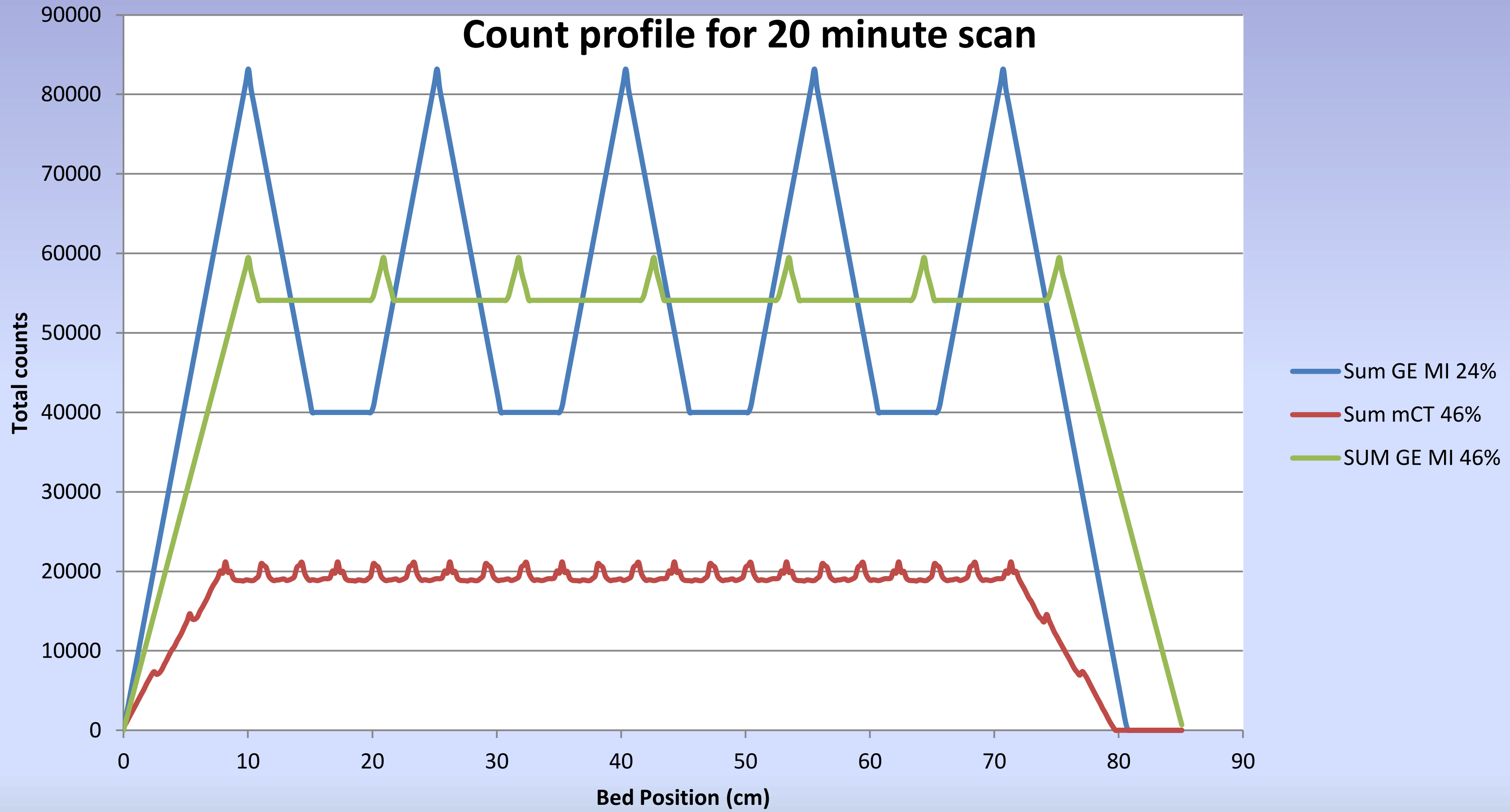
Siemens mCT 46% Bed Overlap
Sensitivity (C/s/MBq)
160
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
80
90
Bed position (cm)
Bed 1
Bed 2

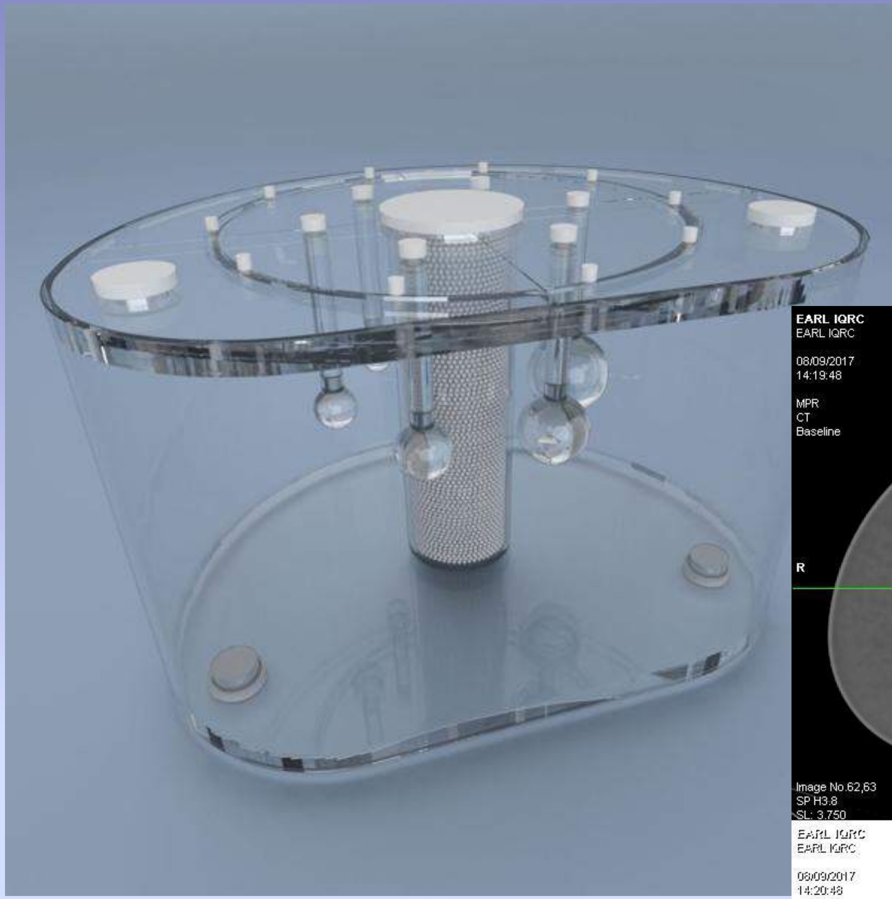

Siemens mCT 46% Bed Overlap
Sensitivity (C/s/MBq)
Bed position (cm)
Bed 1
Bed 2
Bed 3
Bed 4
Bed 5
Bed 6
Bed 7
Bed 8
Sum mCT 46%

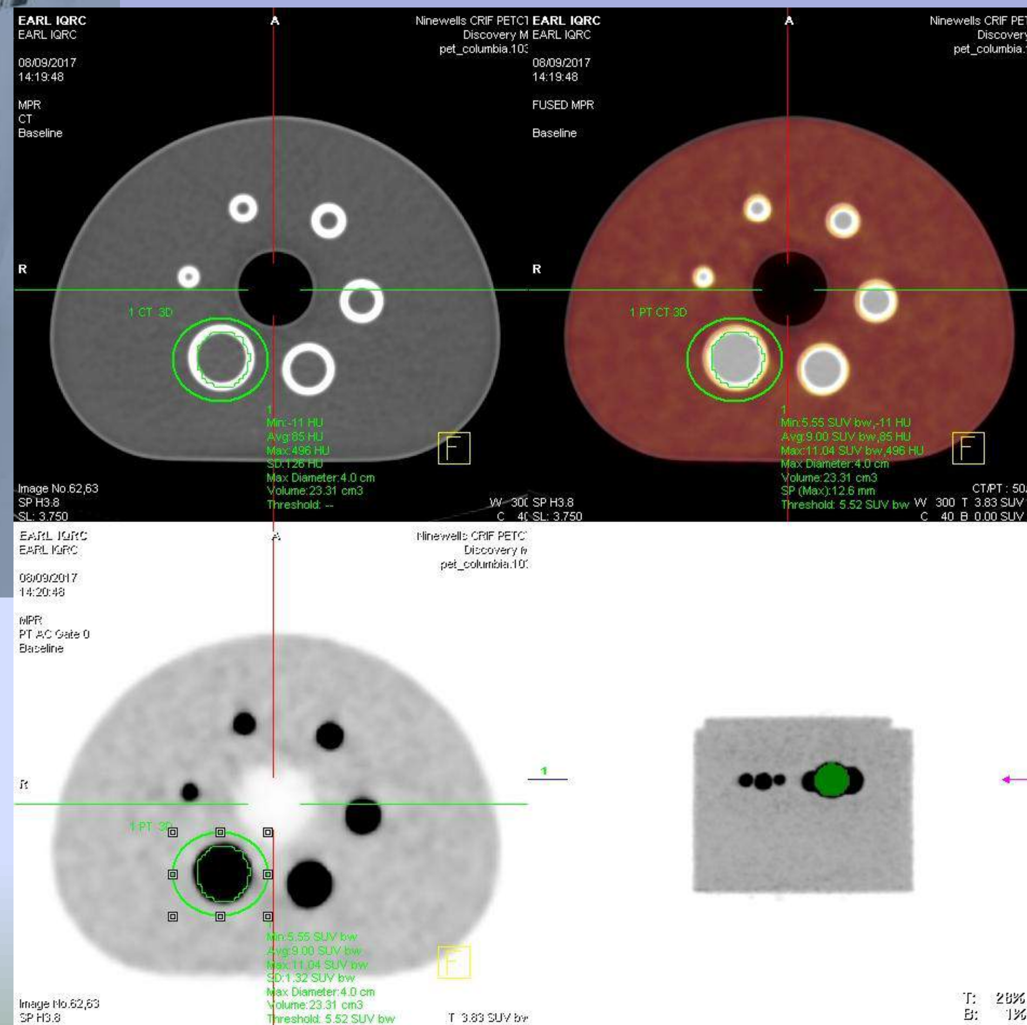

GE MI 24% Bed Overlap
Sensitivity (c/s/MBq)
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
Bed Position (cm)
Bed 1
Bed 2


GE MI 24% Bed Overlap
Sensitivity (c/s/MBq)
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
Bed Position (cm)
Bed 1
Bed 2
Bed 3
Bed 4
Bed 5
Sum GE MI 24%

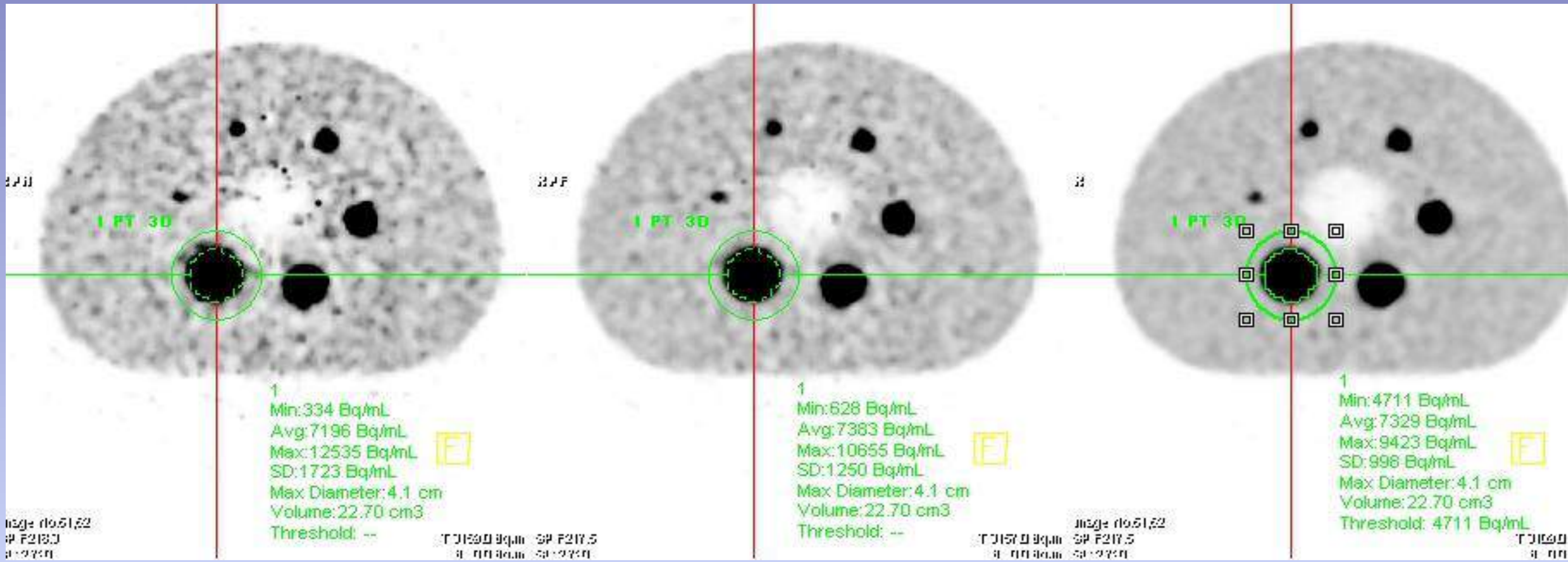

H
2 PT 3D
2
Min:7 Bq/mL
Avg:108 Bq/mL
Max:1486 Bq/mL
SD:172 Bq/mL
Max Diameter:4.
Volume:15.49 cm
1 PT 3D
1
Min:7 Bq/mL
Avg:101 Bq/mL
Max:847 Bq/mL
SD:86 Bq/mL
Max Diameter:4.
Volume:15.95 cm
H
2 PT 3D
2
Min:7 Bq/mL
Avg:12653 Bq/mL
Max:275453 Bq/mL
SD:42548 Bq/mL
Max Diameter:4.6 cm
Volume:15.49 cm3
1 PT 3D
1
Min:7 Bq/mL
Avg:10298 Bq/mL
Max:217236 Bq/mL
SD:39360 Bq/mL
Max Diameter:4.6 cm
Volume:15.95 cm3


Count profile for 20 minute scan
Total counts
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
0
10
20
30
40
50
60
70
80
90
Bed Position (cm)
Sum GE MI 24%
Sum mCT 46%
SUM GE MI 46%

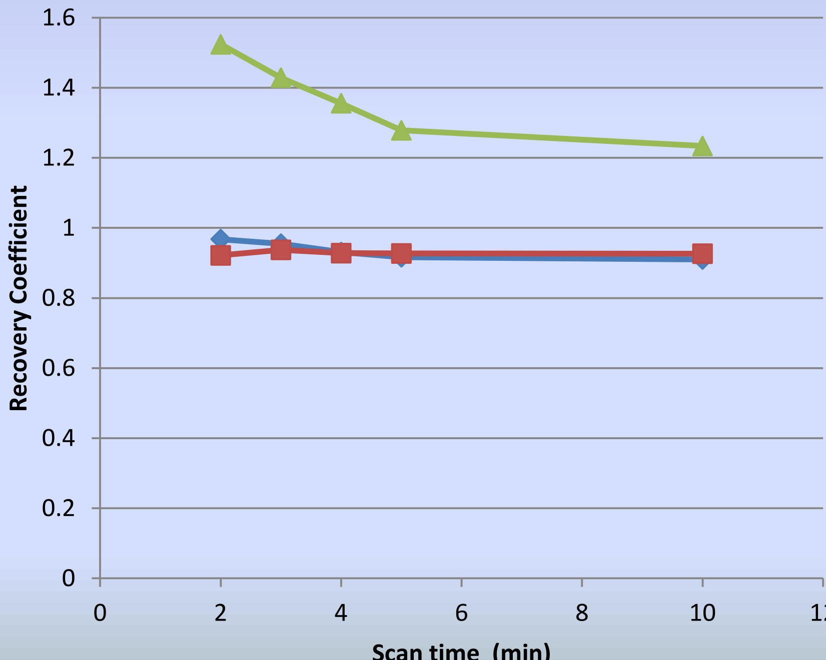




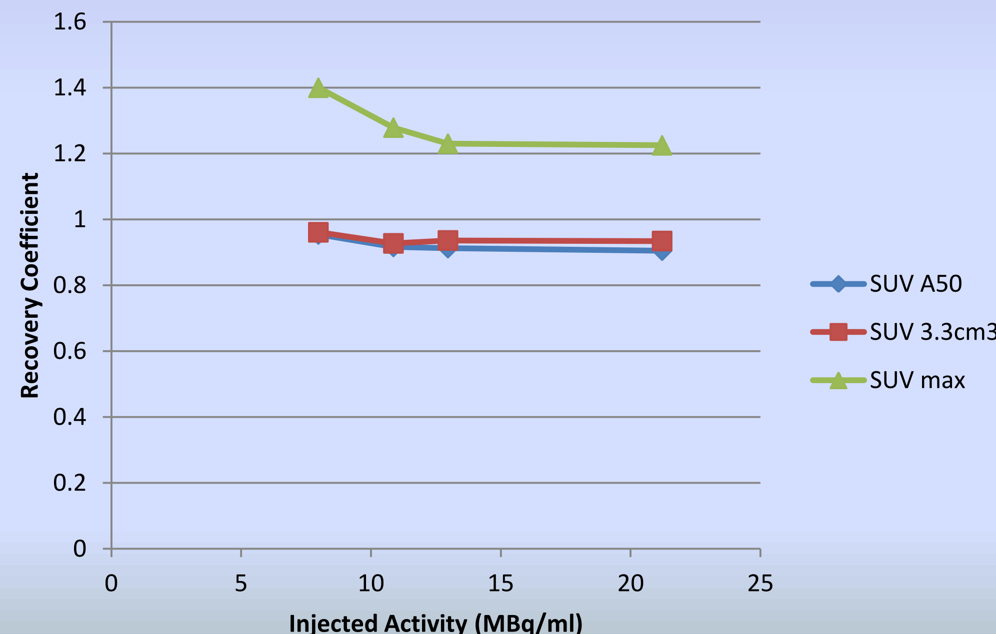
EARL IQRC
EARL IQRC
08/09/2017
14:19:48
MPR
CT
Baseline
A
R
1 CT 3D
1
Min:-11 HU
Avg:85 HU
Max:496 HU
SD:126 HU
Max Diameter:4.0 cm
Volume:23.31 cm3
Threshold: --
Image No.62,63
SP H3.8
SL: 3.750
EARL IQRC
EARL IQRC
08/09/2017
14:19:48
FUSED MPR
Baseline
1 PT CT 3D
1
Min:5.55 SUV bw,-11 HU
Avg:9.00 SUV bw,85 HU
Max:11.04 SUV bw,496 HU
Max Diameter:4.0 cm
Volume:23.31 cm3
SP (Max):12.6 mm
Threshold: 5.52 SUV bw
SP H3.8
SL: 3.750
W 300 T 3.83 SUV bw
C 40 B 0.00 SUV bw
EARL IQRC
EARL IQRC
08/09/2017
14:20:48
MPR
PT AC Gate 0
Baseline
1 PT 3D
Min:5.55 SUV bw
Avg:9.00 SUV bw
Max:11.04 SUV bw
SD:1.32 SUV bw
Max Diameter:4.0 cm
Volume:23.31 cm3
Threshold: 5.52 SUV bw
Image No.62,63
SP H3.8
SL: 2.790
T 3.83 SUV bw
B 0.00 SUV bw
T: 28%
B: 1%



1 PT 3D
1
Min:334 Bq/mL
Avg:7196 Bq/mL
Max:12535 Bq/mL
SD:1723 Bq/mL
Max Diameter:4.1 cm
Volume:22.70 cm3
Threshold: --
1 PT 3D
1
Min:628 Bq/mL
Avg:7383 Bq/mL
Max:10655 Bq/mL
SD:1250 Bq/mL
Max Diameter:4.1 cm
Volume:22.70 cm3
Threshold: --
1 PT 3D
1
Min:4711 Bq/mL
Avg:7329 Bq/mL
Max:9423 Bq/mL
SD:998 Bq/mL
Max Diameter:4.1 cm
Volume:22.70 cm3
Threshold: 4711 Bq/mL

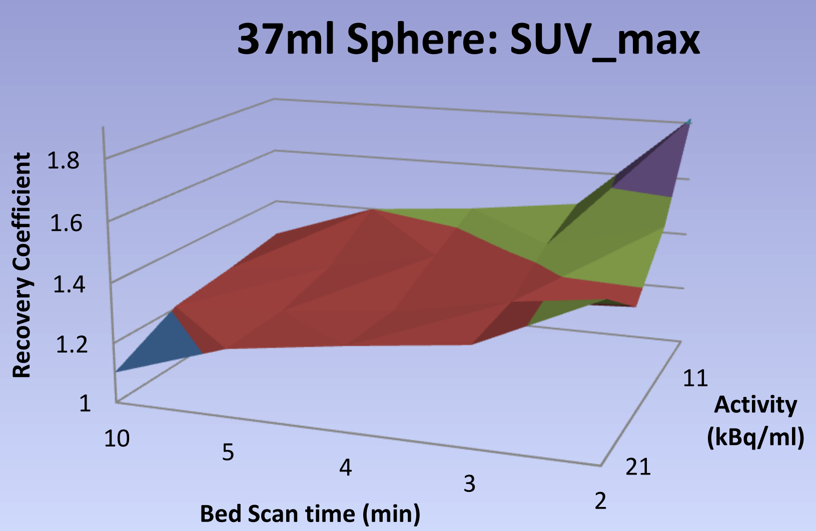


Recovery Coefficient
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
Scan time (min)

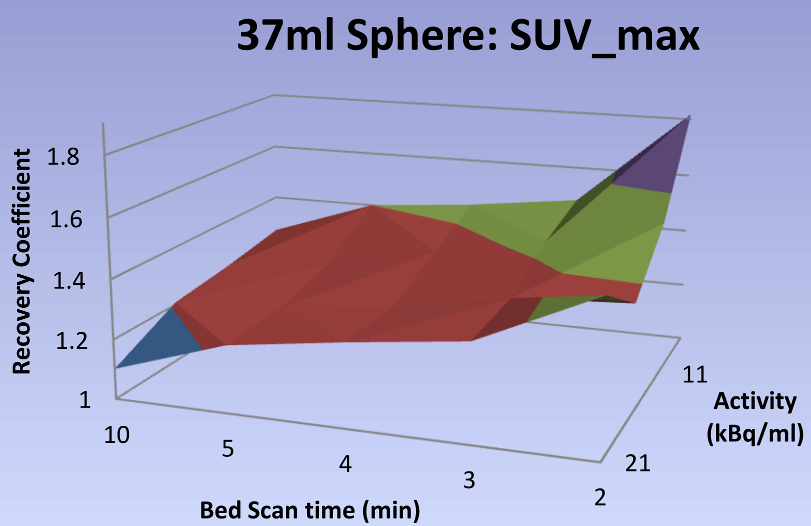


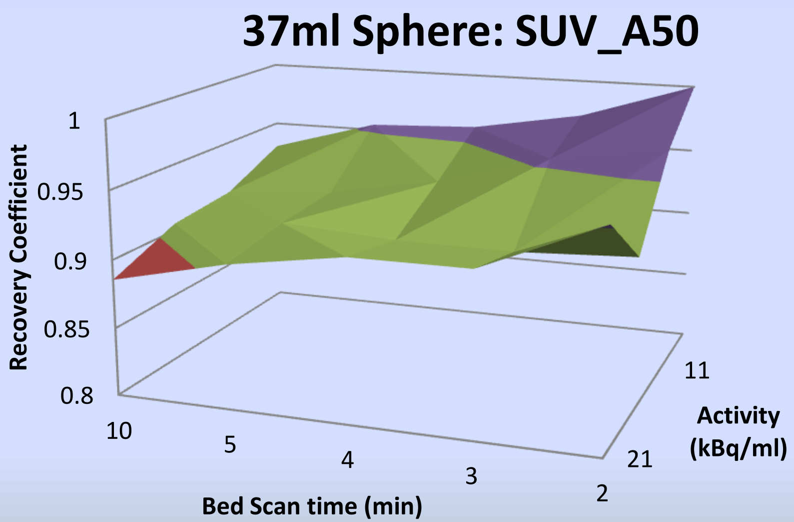
Recovery Coefficient
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
Injected Activity (MBq/ml)
SUV A50
SUV 3.3cm3
SUV max

OSEM ToF Reconstruction

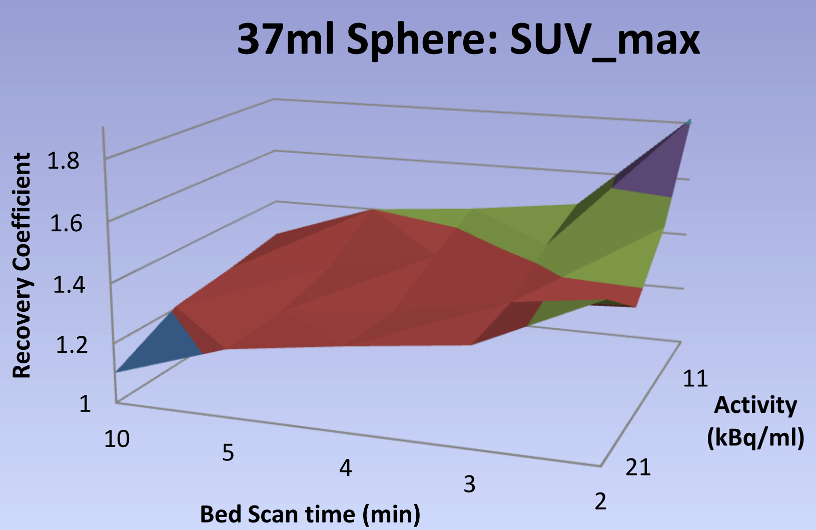


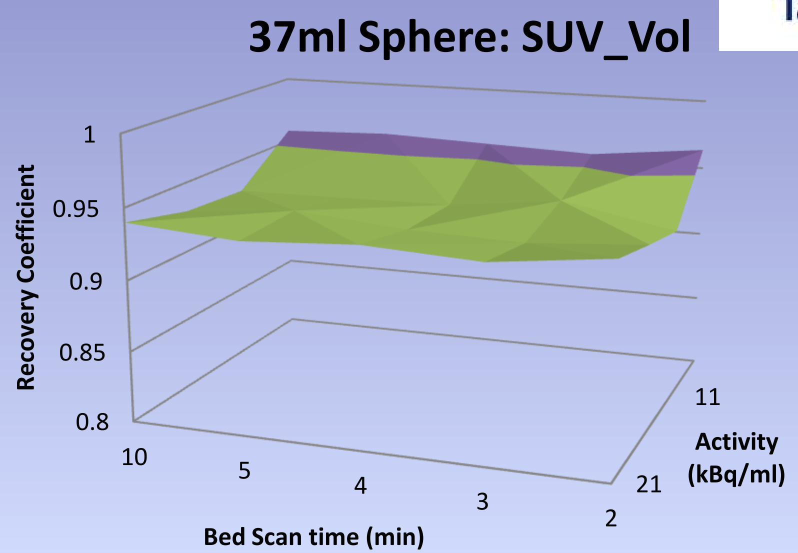
OSEM ToF Reconstruction

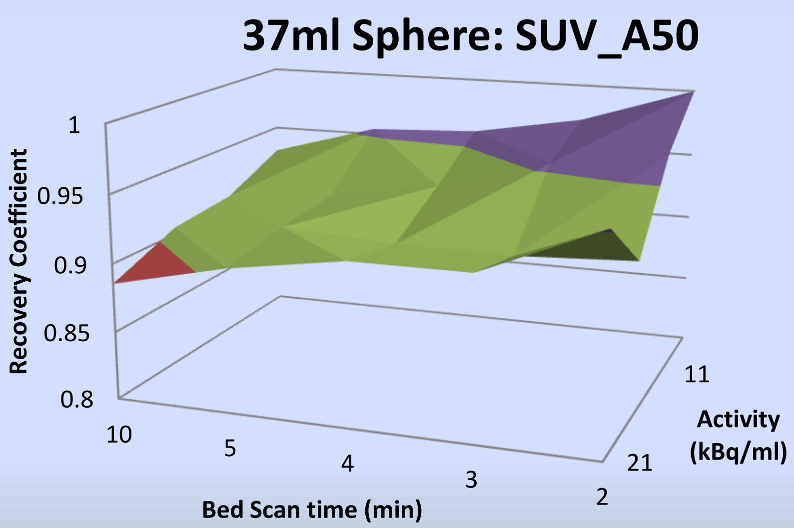




OSEM ToF Reconstruction

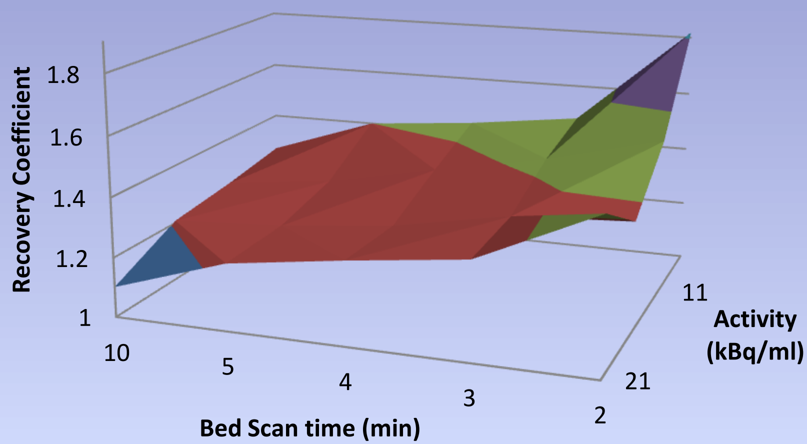




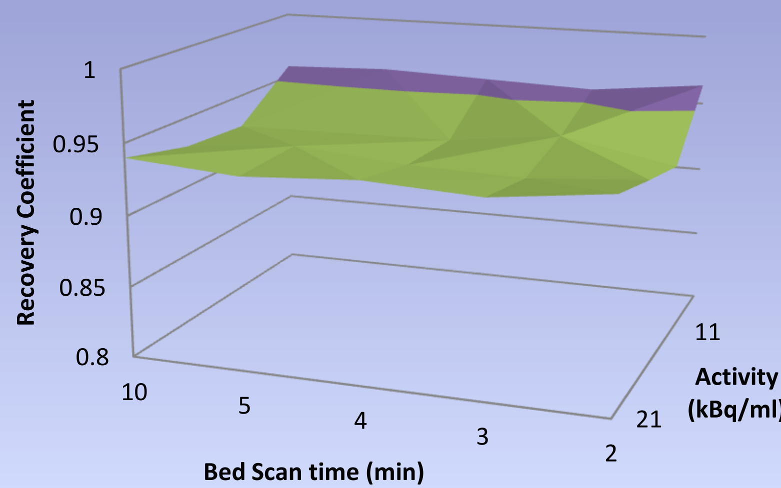


OSEM ToF Reconstruction

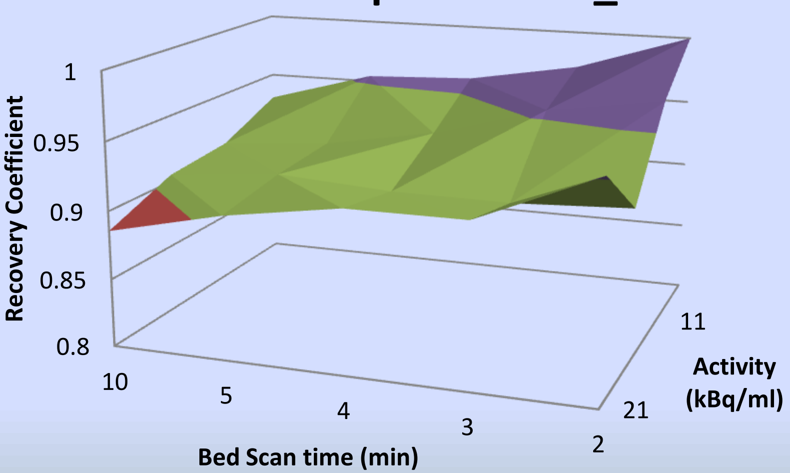
37ml Sphere: SUV_max



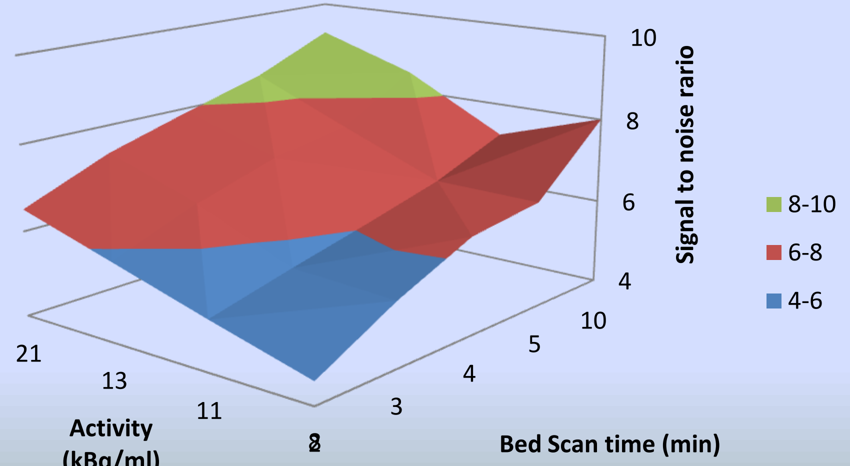
37ml Sphere: SUV_Vol



37ml Sphere: SUV_A50

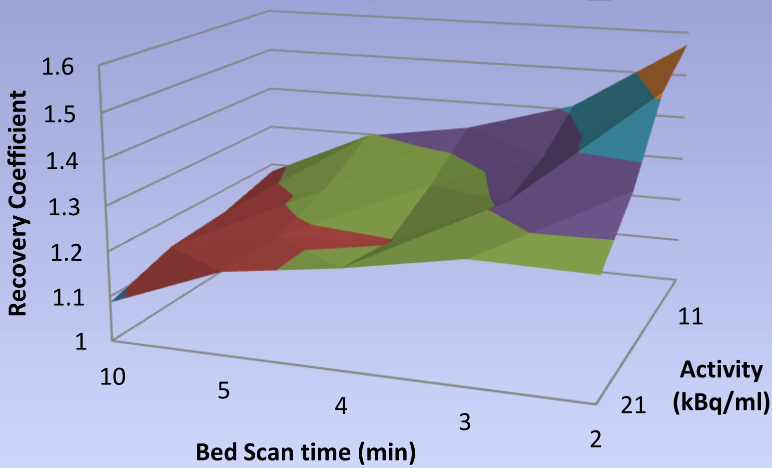


37ml Sphere: SNR SUV_vol

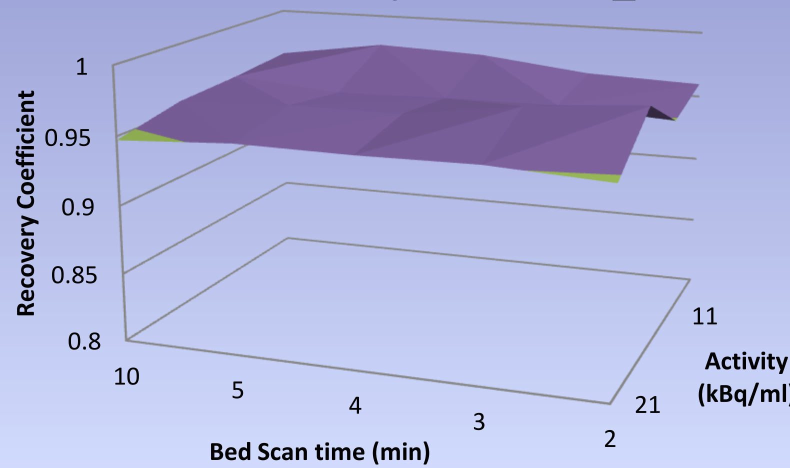


Q400 Reconstruction

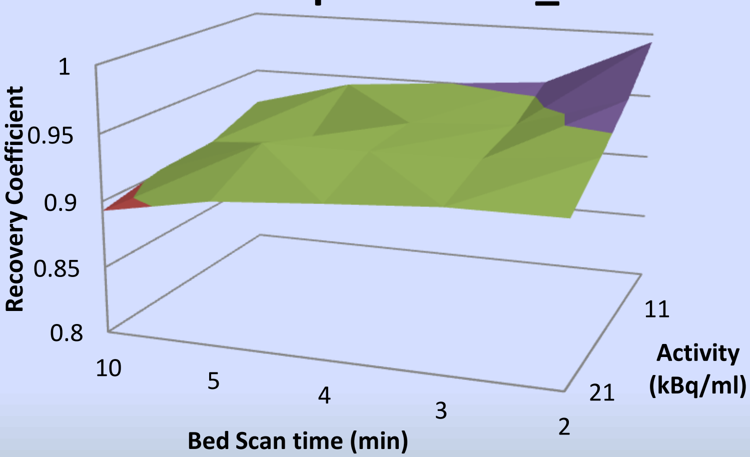
37ml Sphere: SUV_max



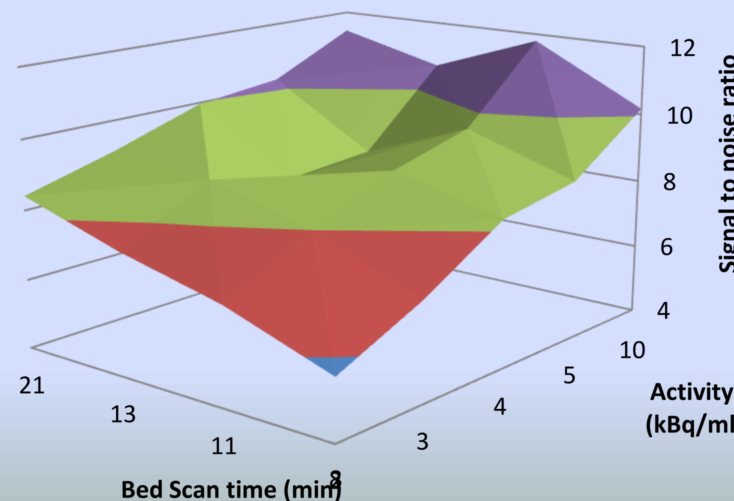
37ml Sphere: SUV_Vol



37ml Sphere: SUV_A50

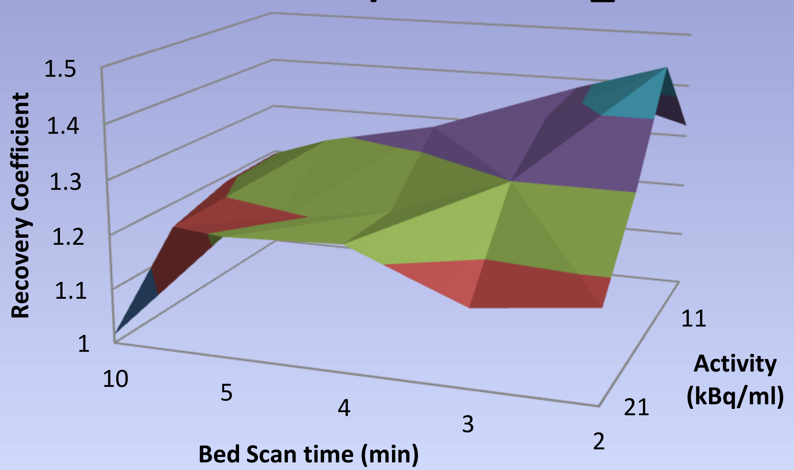


37ml Sphere: SNR SUV_vol

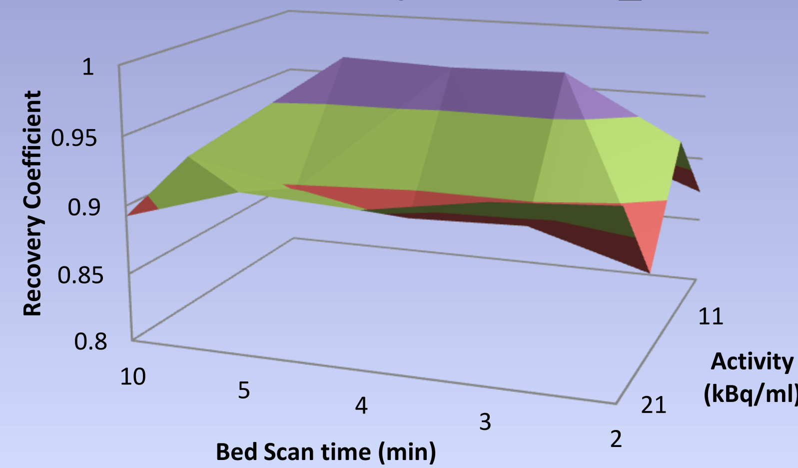


Q400 Reconstruction

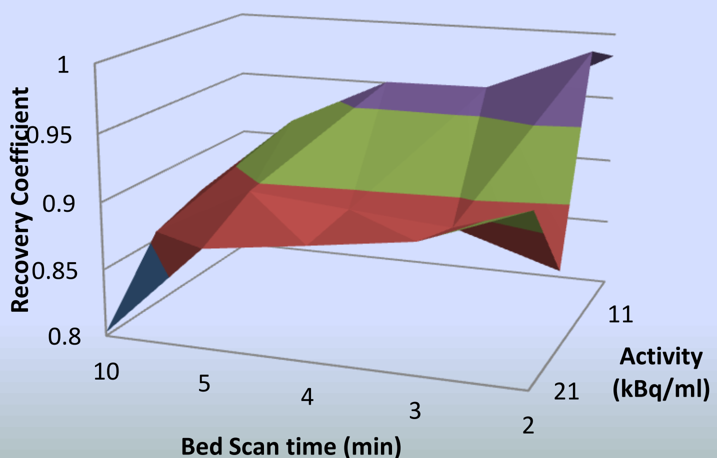
17ml Sphere: SUV_max



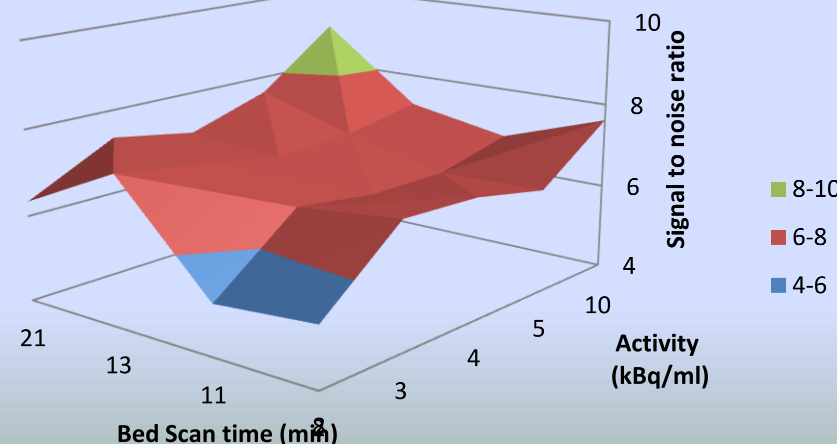
17ml Sphere: SUV_Vol



17ml Sphere: SUV_A50



17ml Sphere: SNR SUV_max



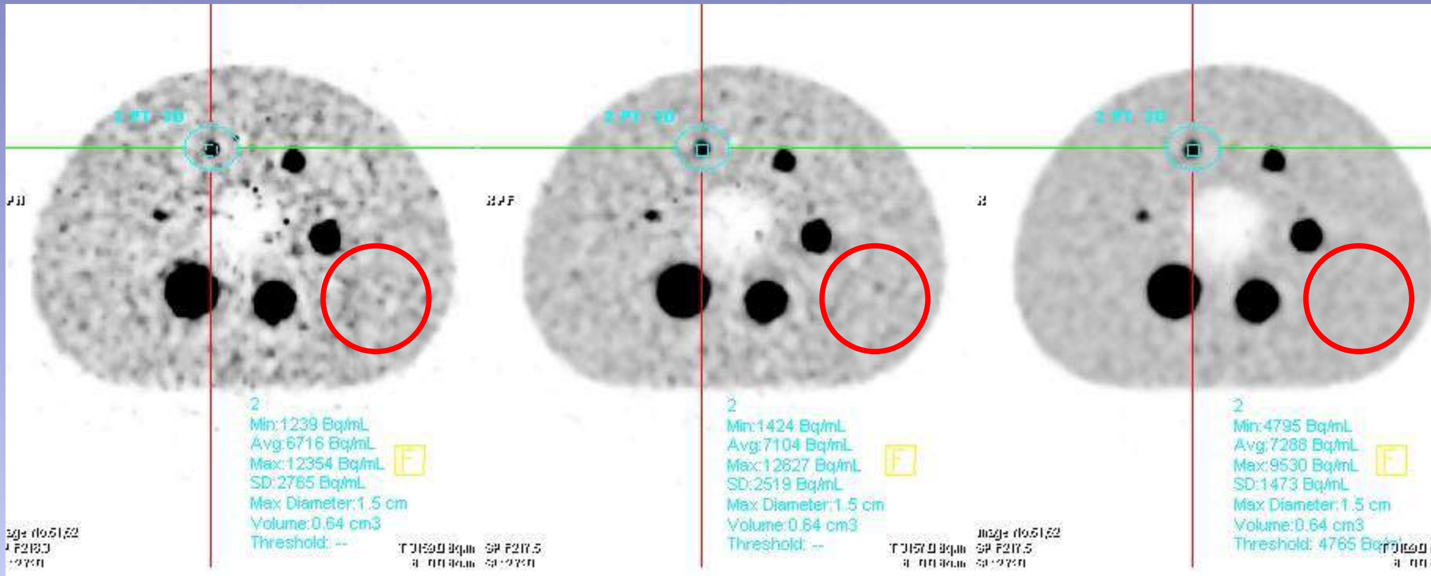


Image Noise (ToF)

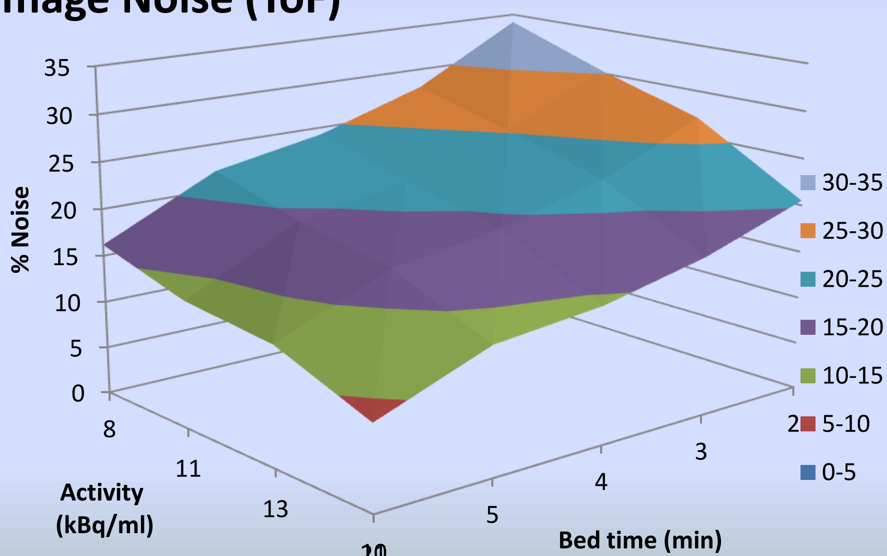
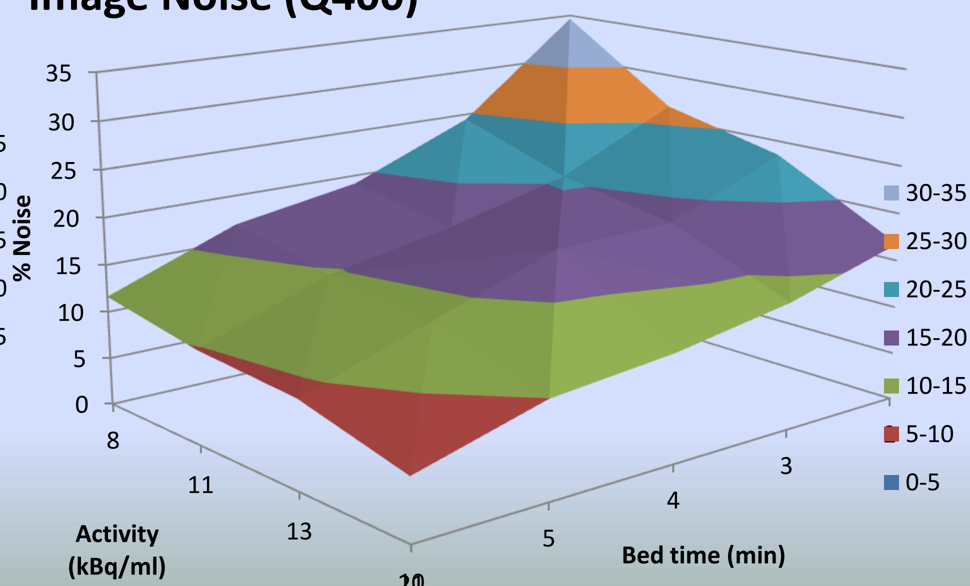
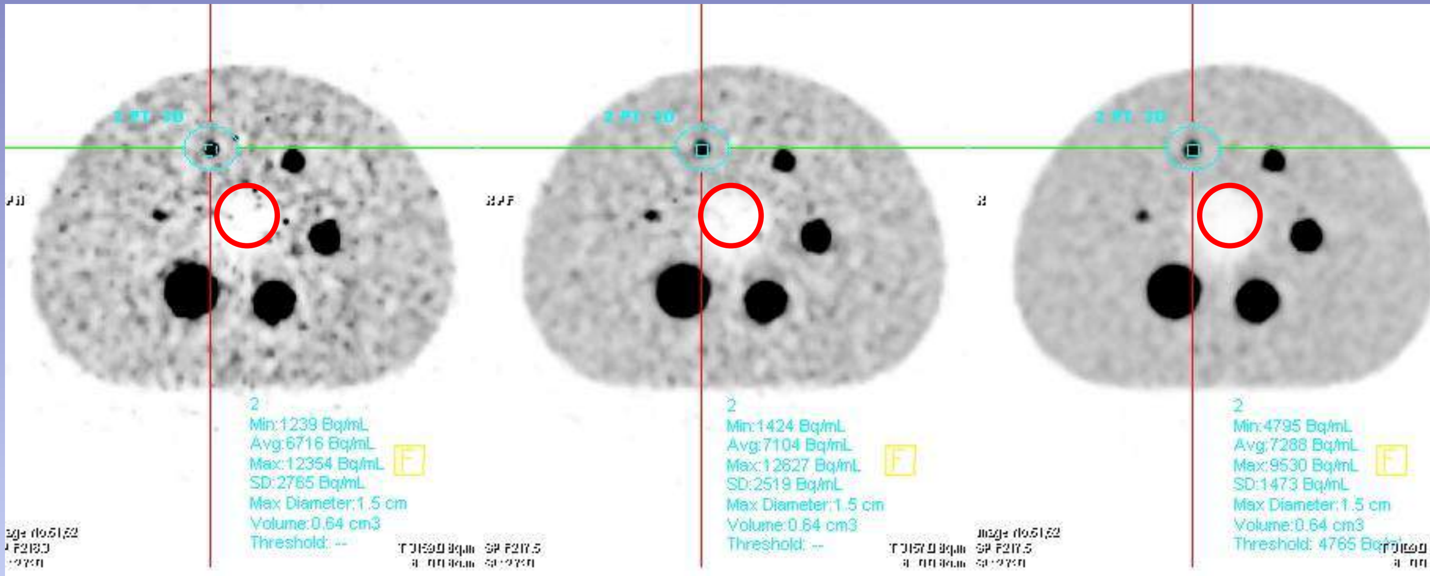


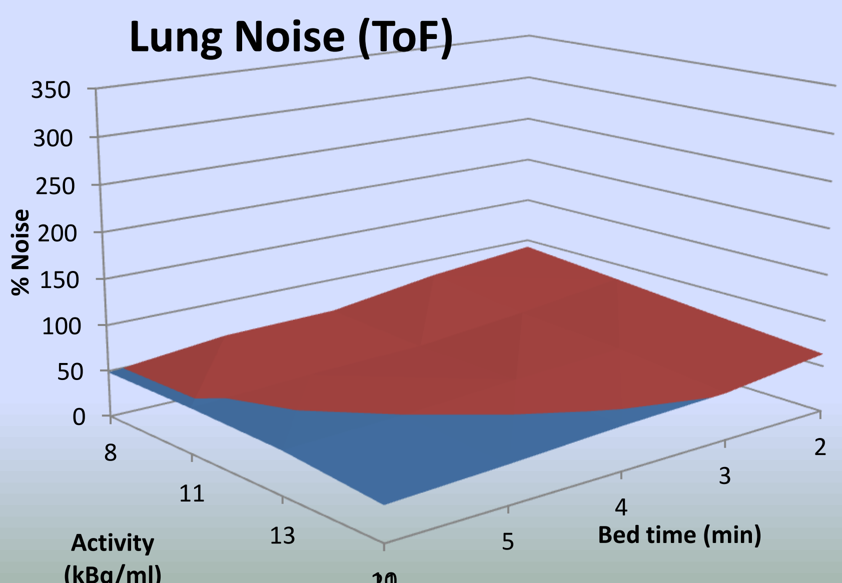
Image Noise (Q400)



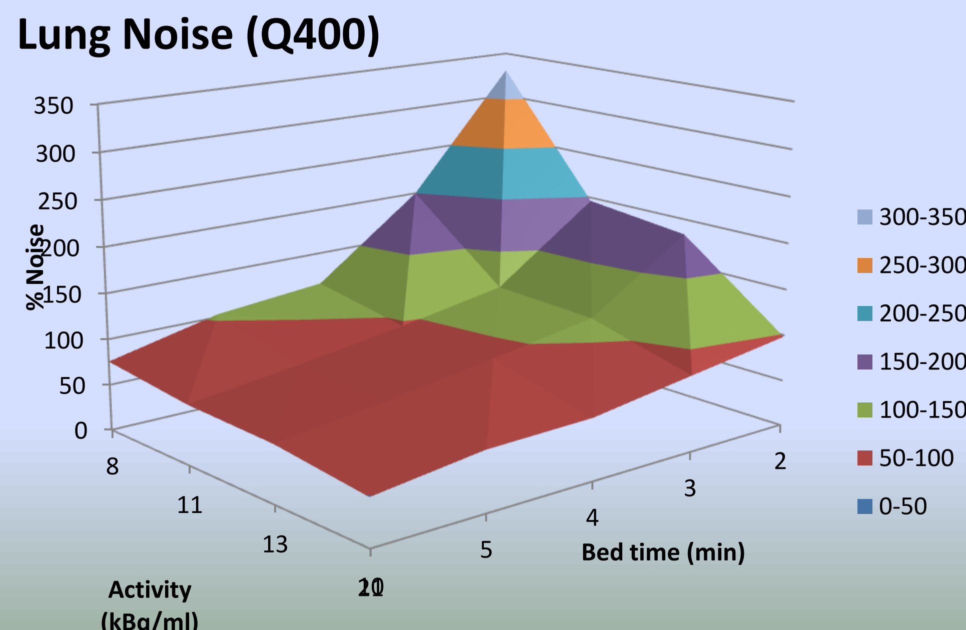
NHS Tayside



2
Min:1239 Bq/mL
Avg:6716 Bq/mL
Max:12354 Bq/mL
SD:2765 Bq/mL
Max Diameter:1.5 cm
Volume:0.64 cm3
Threshold: --
2
Min:1424 Bq/mL
Avg:7104 Bq/mL
Max:12627 Bq/mL
SD:2519 Bq/mL
Max Diameter:1.5 cm
Volume:0.64 cm3
Threshold: --
2
Min:4795 Bq/mL
Avg:7288 Bq/mL
Max:9530 Bq/mL
SD:1473 Bq/mL
Max Diameter:1.5 cm
Volume:0.64 cm3
Threshold: 4765



Lung Noise (ToF)
% Noise
0
50
100
150
200
250
300
350
Activity (kBq/ml)
8
11
13
20
Bed time (min)
2
3
4
5



Lung Noise (Q400)
% Noise
0
50
100
150
200
250
300
350
Activity (kBq/ml)
8
11
13
20
Bed time (min)
2
3
4
5
300-350
250-300
200-250
150-200
100-150
50-100
0-50

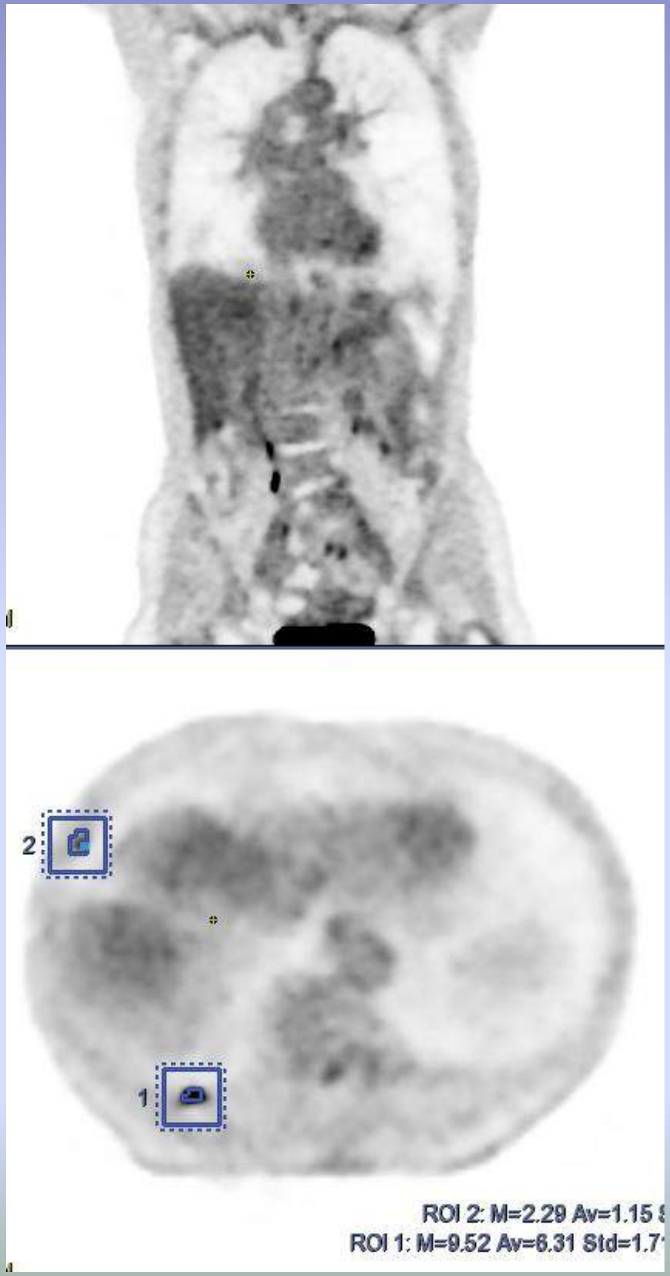
NHS Tayside Protocol:

NHS Tayside

34 slice overlap

3 minutes bed time (4min for BMI>30)

3MBq/kg   (minimum 200 MBq)

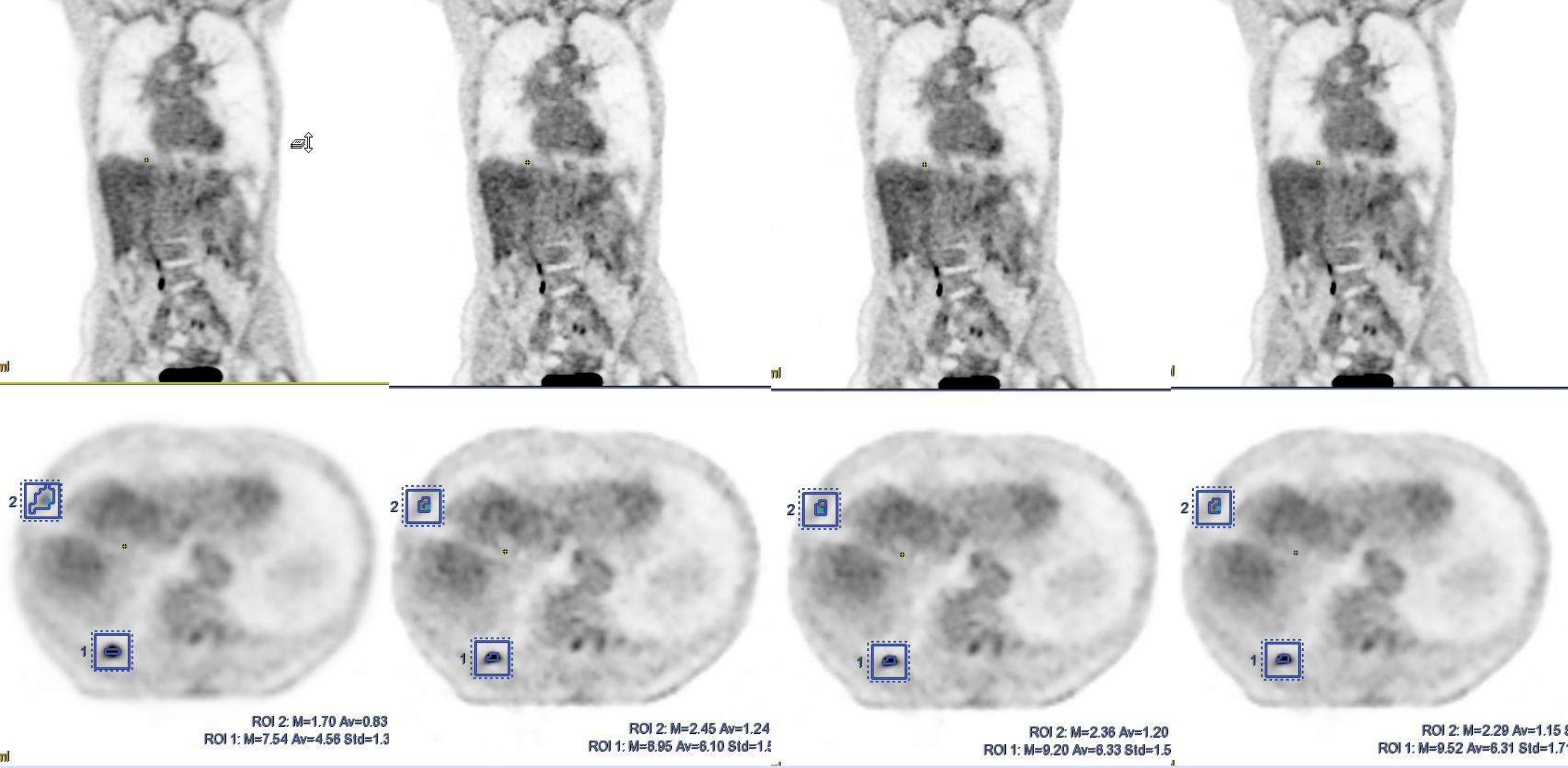


ARSAC

For systems that apply a PET bed overlap of >30 %, the minimum FDG administered activity is calculated as follows:

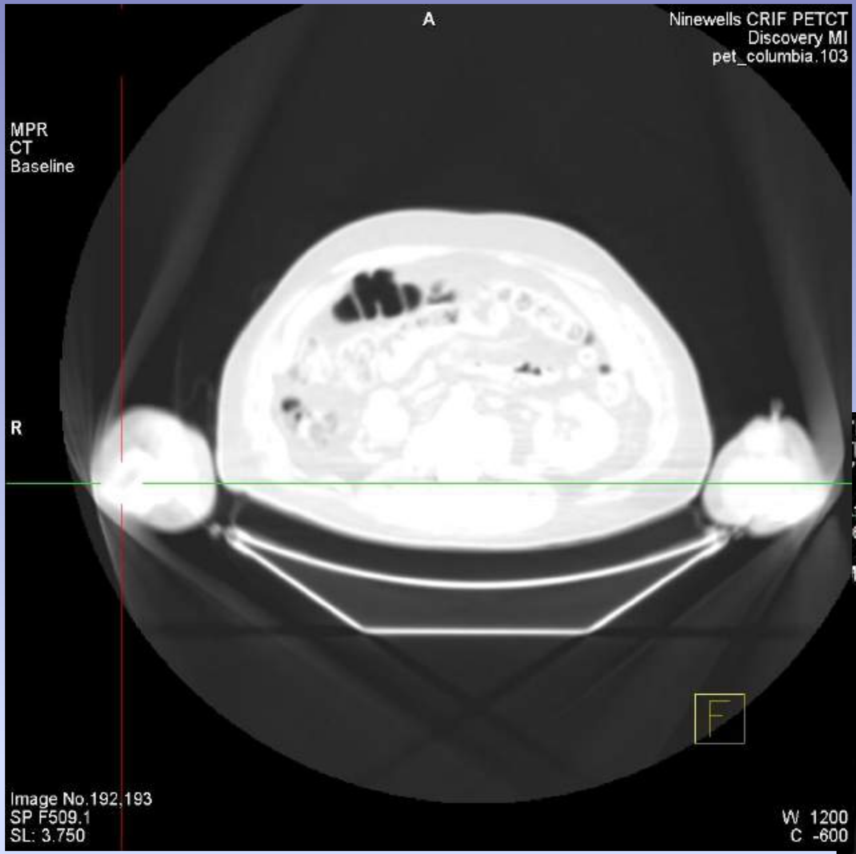
FDG (MBq) = 7 (MBq·min·bed−1·kg−1) × patient weight (kg)/emission acquisition duration per bed position (min·bed−1)

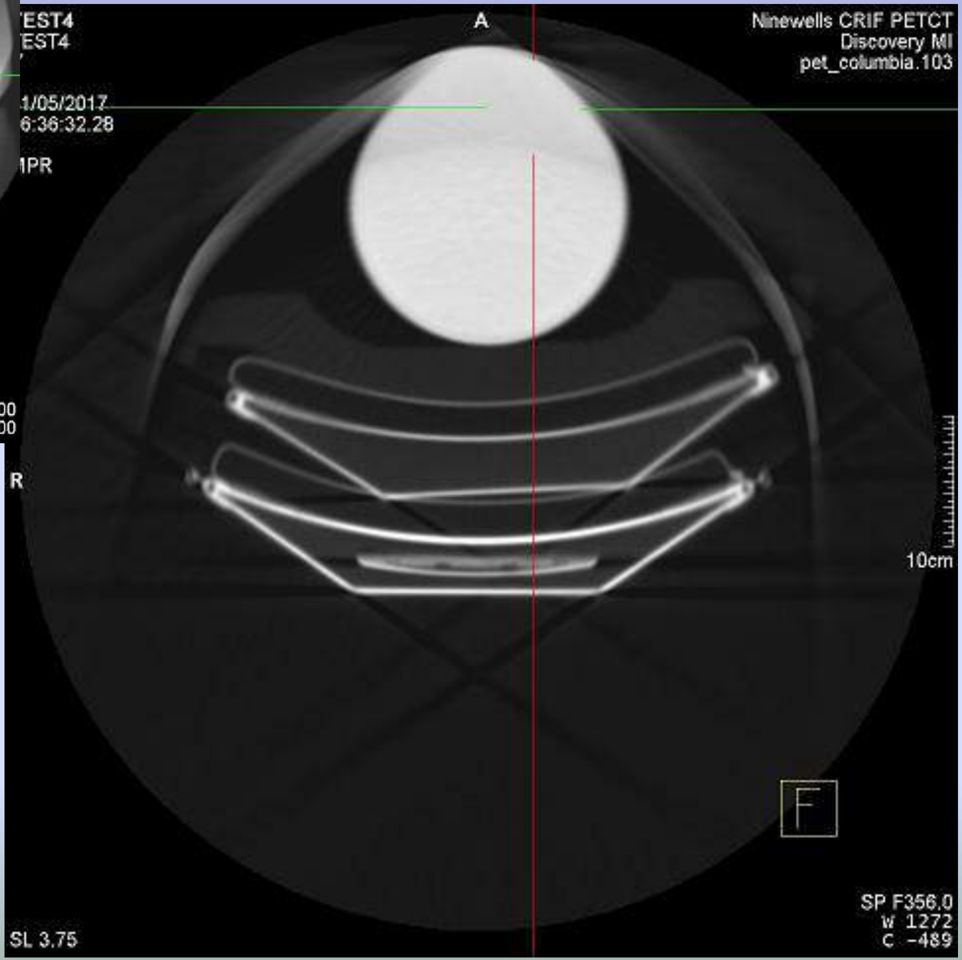
i.e. ~2.5 MBq/kg   minimum

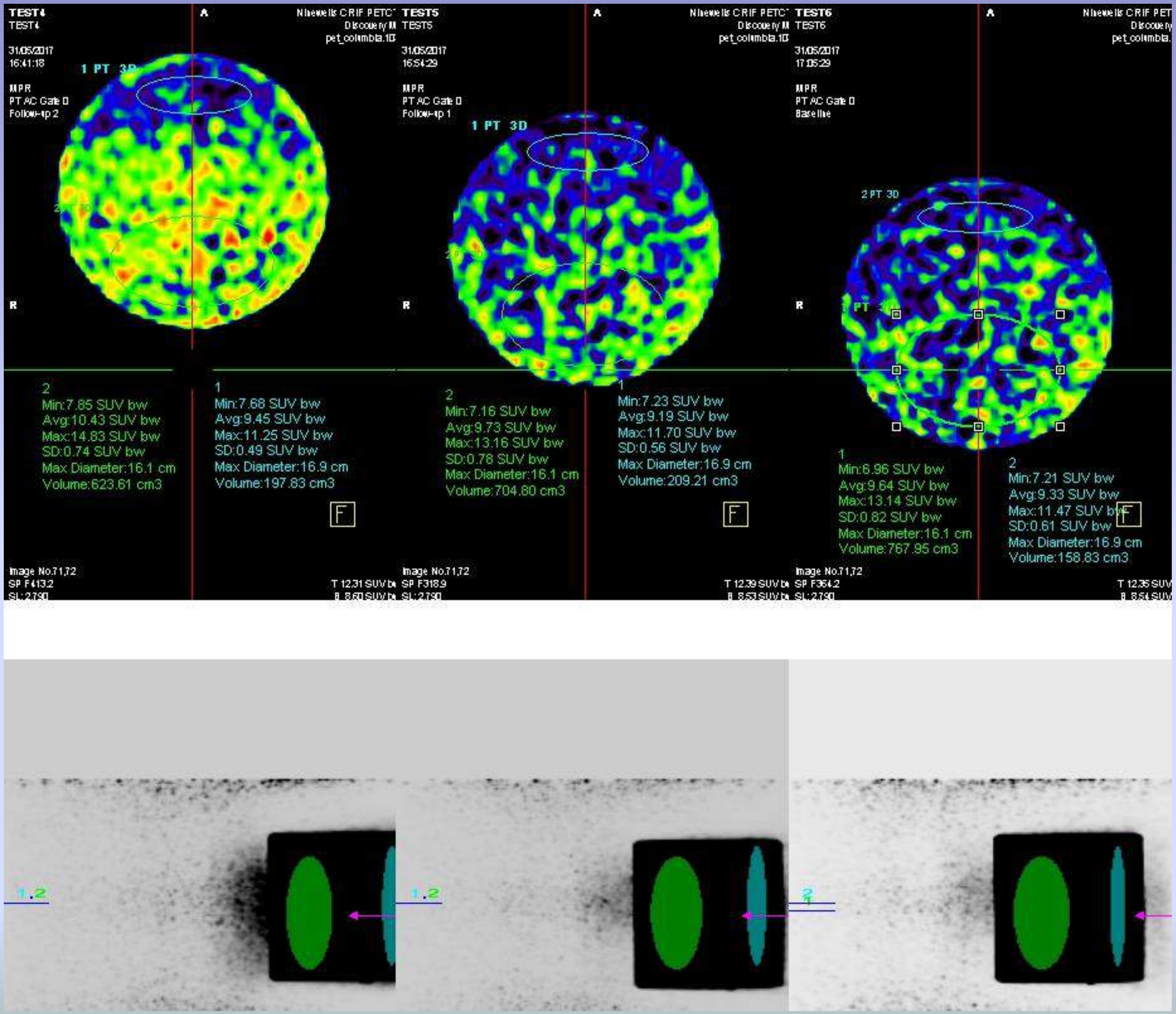


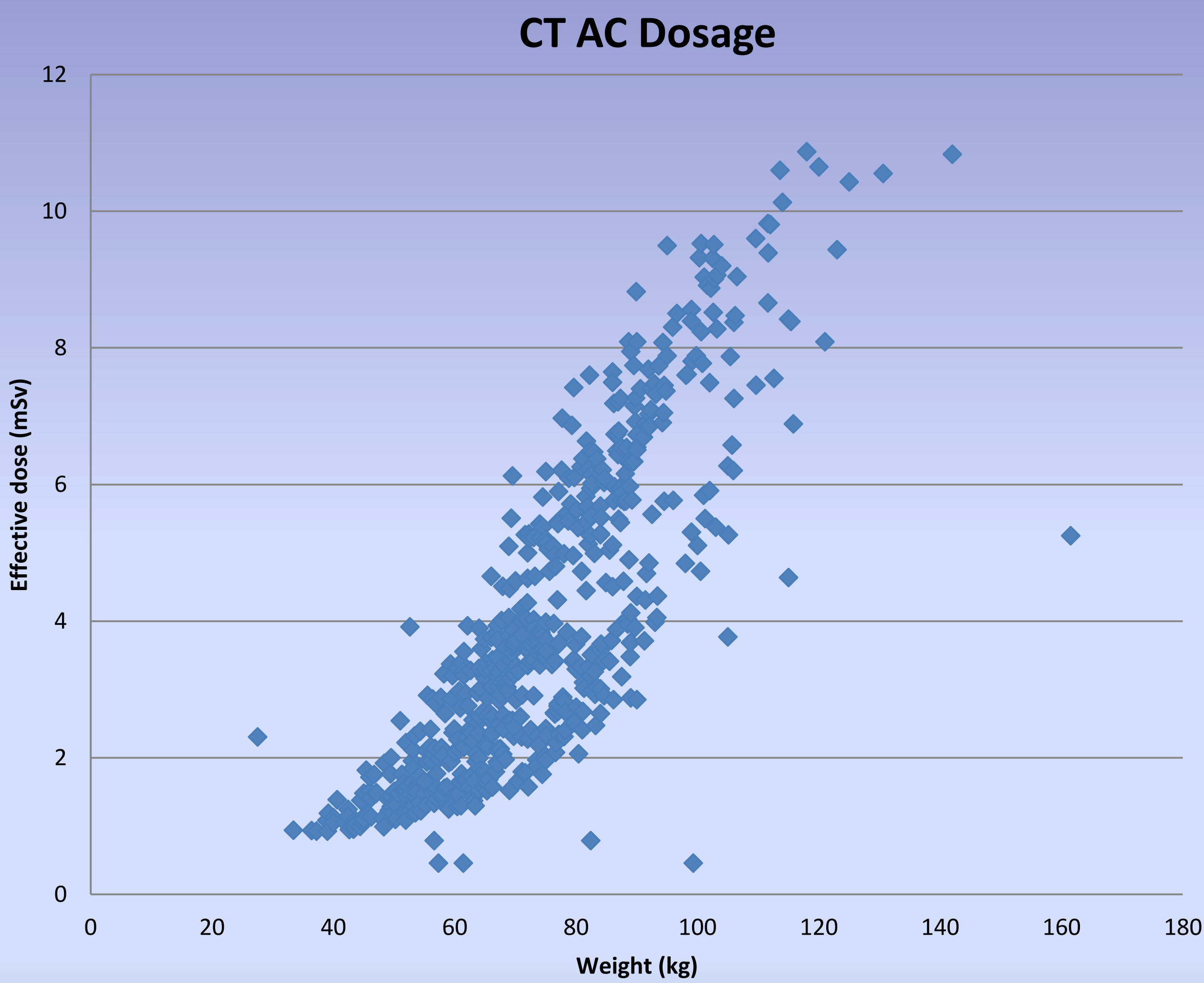
Patient	Weight (kg)	Scan dose (MBq)	3 MBq/kg	2.5 MBq/kg
1	54	201	162	135
2	64	201	195	160
3	61	209	183	153
4	60	206	180	150
5	57	207	171	143
6	50	204	150	125

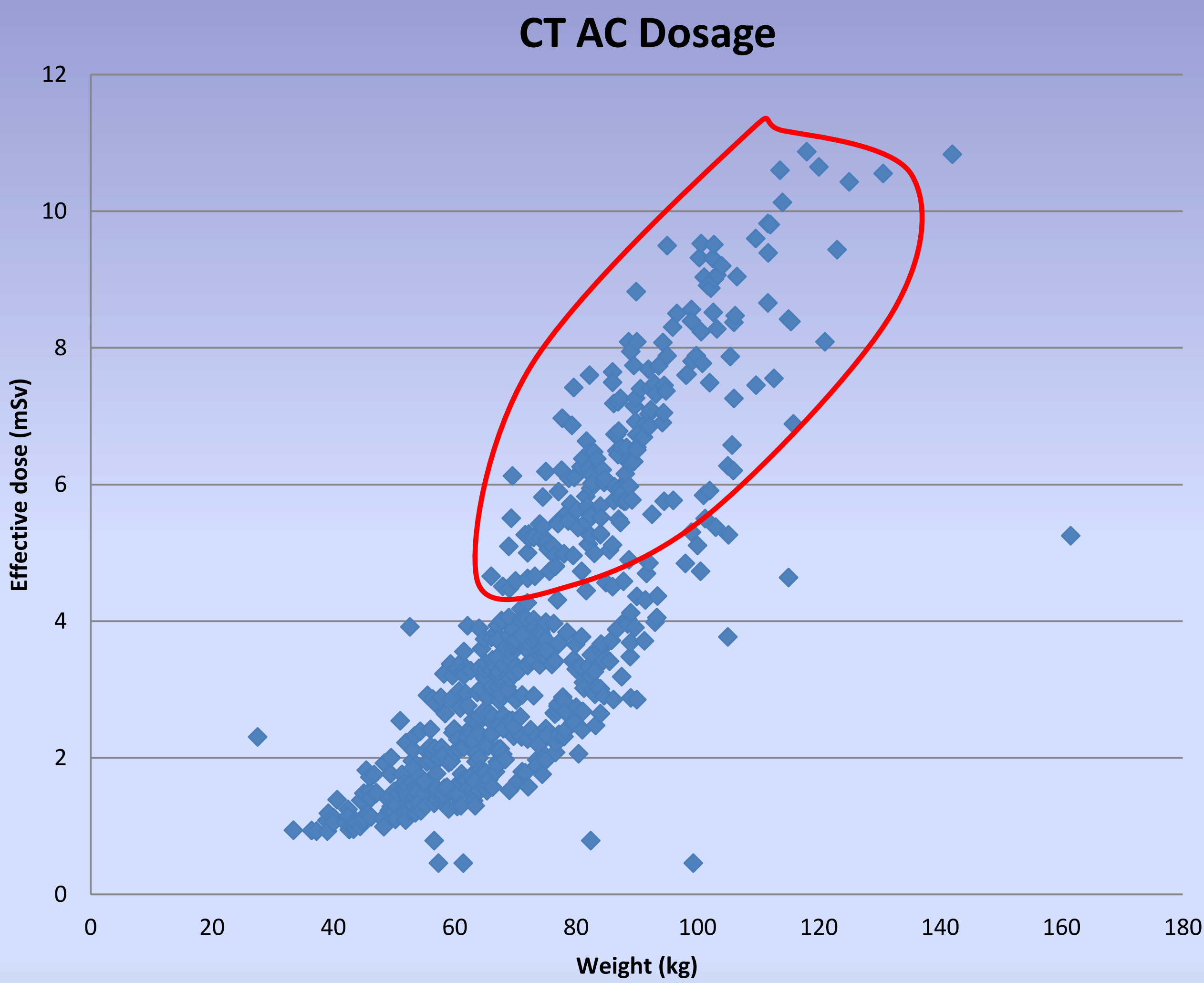
	osem	Q-200MBq	Q-3MBq/kg	Q-2.5MBq/kg
Most fav	2.5	6.5	5.5	8.5
Least Fav	10	2	5	5


A
Ninewells CRIF PETCT
Discovery MI
pet_columbia.103
MPR
CT
Baseline
R
Image No.192,193
SP F509.1
SL: 3.750
W 1200
C -600


A
Ninewells CRIF PETCT
Discovery MI
pet_columbia.103
R
10cm
SL 3.75
SP F356.0
W 1272
C -489


TEST4
1 PT 3D
MPR
PT AC Gate 0
Follow-up 2
R
A
2
Min:7.85 SUV bw
Avg:10.43 SUV bw
Max:14.83 SUV bw
SD:0.74 SUV bw
Max Diameter:16.1 cm
Volume:623.61 cm3
1
Min:7.68 SUV bw
Avg:9.45 SUV bw
Max:11.25 SUV bw
SD:0.49 SUV bw
Max Diameter:16.9 cm
Volume:197.83 cm3
F
TEST5
1 PT 3D
MPR
PT AC Gate 0
Follow-up 1
2
Min:7.16 SUV bw
Avg:9.73 SUV bw
Max:13.16 SUV bw
SD:0.78 SUV bw
Max Diameter:16.1 cm
Volume:704.80 cm3
1
Min:7.23 SUV bw
Avg:9.19 SUV bw
Max:11.70 SUV bw
SD:0.56 SUV bw
Max Diameter:16.9 cm
Volume:209.21 cm3
F
TEST6
2 PT 3D
MPR
PT AC Gate 0
Baseline
1
Min:6.96 SUV bw
Avg:9.64 SUV bw
Max:13.14 SUV bw
SD:0.82 SUV bw
Max Diameter:16.1 cm
Volume:767.95 cm3
2
Min:7.21 SUV bw
Avg:9.33 SUV bw
Max:11.47 SUV bw
SD:0.61 SUV bw
Max Diameter:16.9 cm
Volume:158.83 cm3
F
1.2
1.2


CT AC Dosage
Effective dose (mSv)
0
2
4
6
8
10
12
Weight (kg)
0
20
40
60
80
100
120
140
160
180

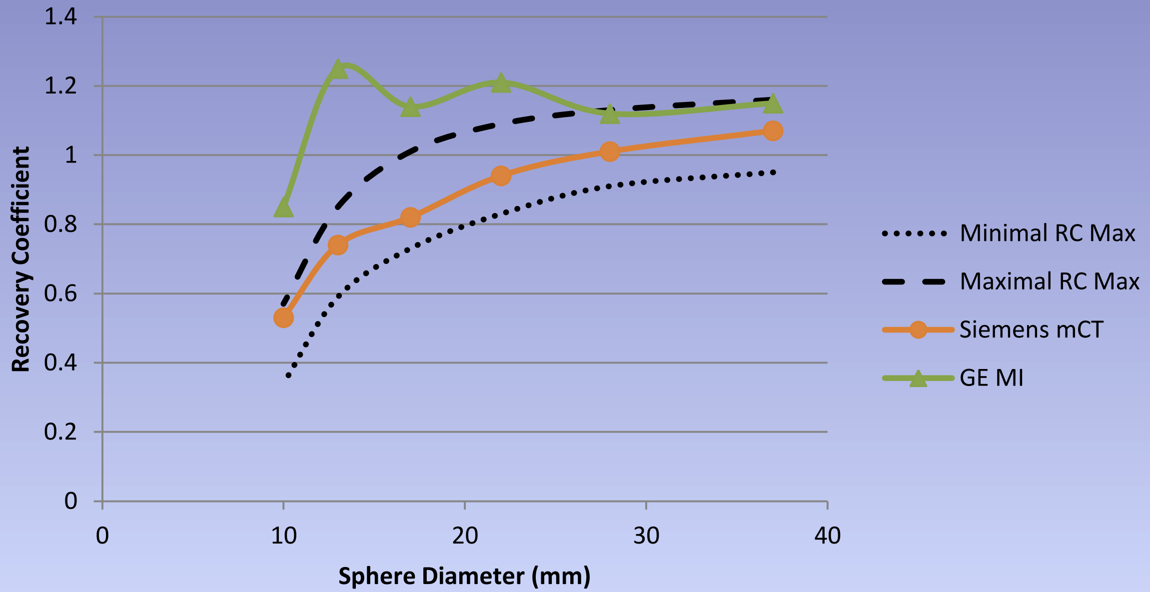

CT AC Dosage
Effective dose (mSv)
0
2
4
6
8
10
12
Weight (kg)
0
20
40
60
80
100
120
140
160
180

QClear 500

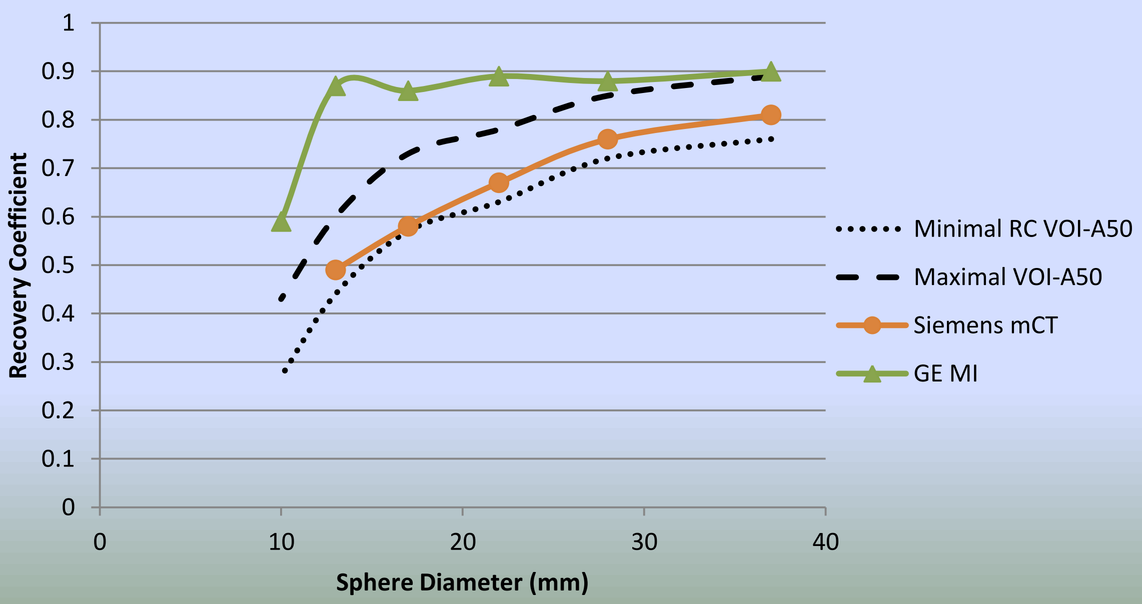
Qclear 400

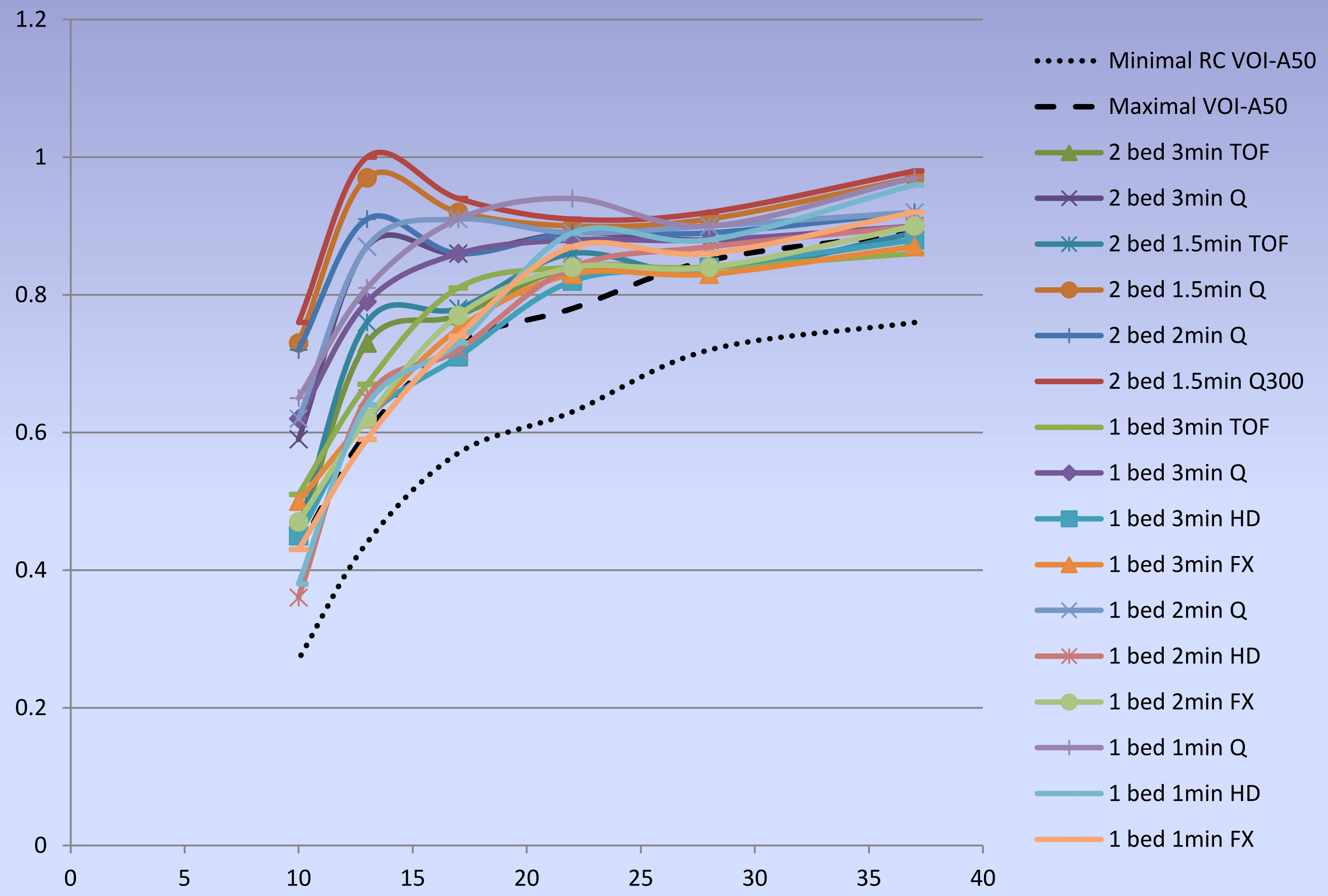
Qclear 300

EARL Accreditation Result (SUV_{max})



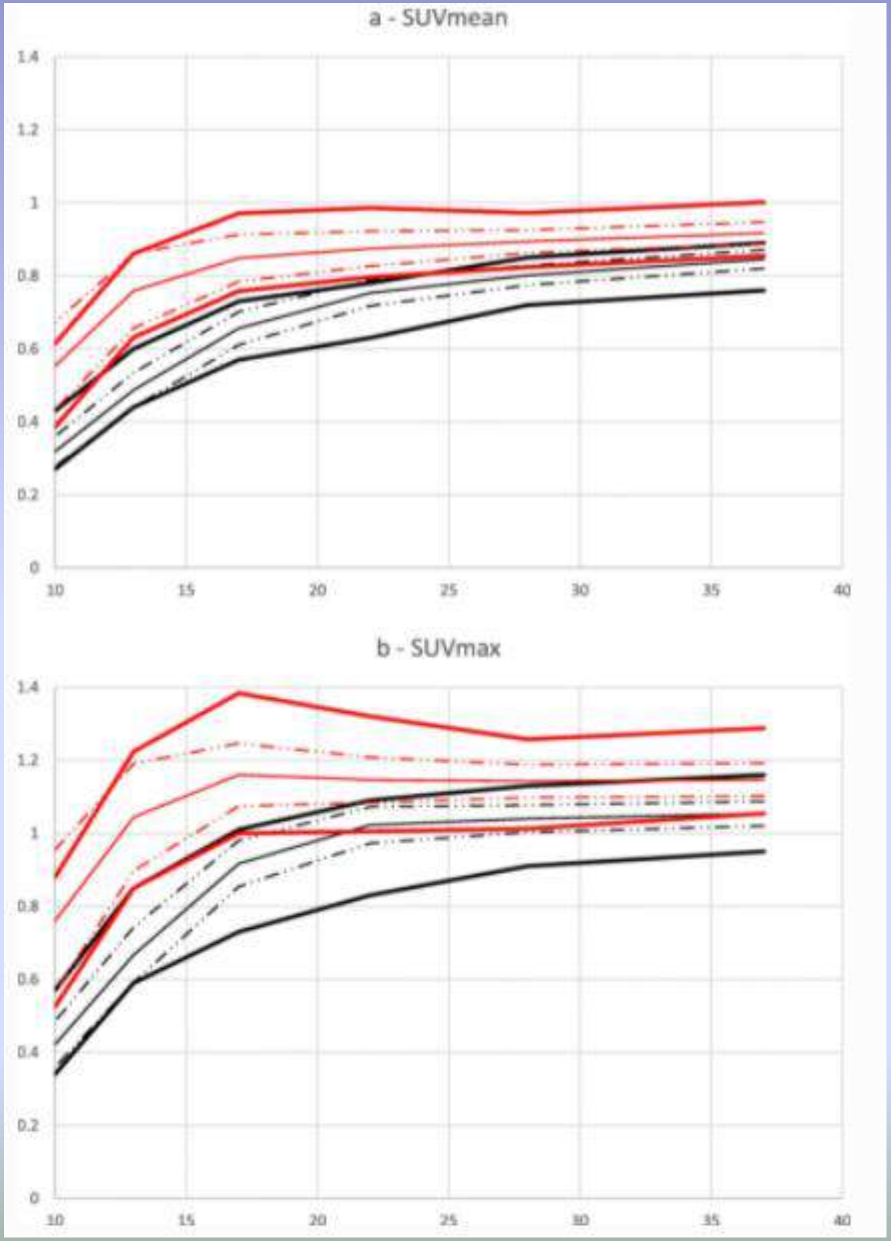
EARL Accreditation Result ($SUV_{ave50\%}$)





1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
40
Minimal RC VOI-A50
Maximal VOI-A50
2 bed 3min TOF
2 bed 3min Q
2 bed 1.5min TOF
2 bed 1.5min Q
2 bed 2min Q
2 bed 1.5min Q300
1 bed 3min TOF
1 bed 3min Q
1 bed 3min HD
1 bed 3min FX
1 bed 2min Q
1 bed 2min HD
1 bed 2min FX
1 bed 1min Q
1 bed 1min HD
1 bed 1min FX

EARL 2019 PET–CT performance standards



Now what does that button do?

IPEM conferences

An Introduction to PET Physics

24th and 25th May 2021, Online

PET Scanner QC and Performance Assessment

Peter Julyan

Christie Medical Physics & Engineering

The Christie NHS FT, Manchester, UK

The Christie NHS

NHS Foundation Trust

IPEM conferences

An Introduction to PET Physics

24th and 25th May 2021, Online

FINAL PROGRAMME

	DAY ONE
13:30 14:00	**An Introduction to PET Physics** Heather Williams, The Christie NHS Foundation Trust
14.00 – 14.30	**PET Scanner QC and performance assessment** Peter Julyan, The Christie NHS Foundation Trust
14.30 – 14.40	**Break**
14.40 – 15.30	**Features of Current Generation PET Systems** Ian Armstrong, Manchester University NHS Foundation Trust and Glen Gardner, NHS Tayside
15.30 – 16.15	**Radiation Protection in PETCT** Andy Bradley, Manchester University NHS Foundation Trust
16.15 – 16.30	**Questions**

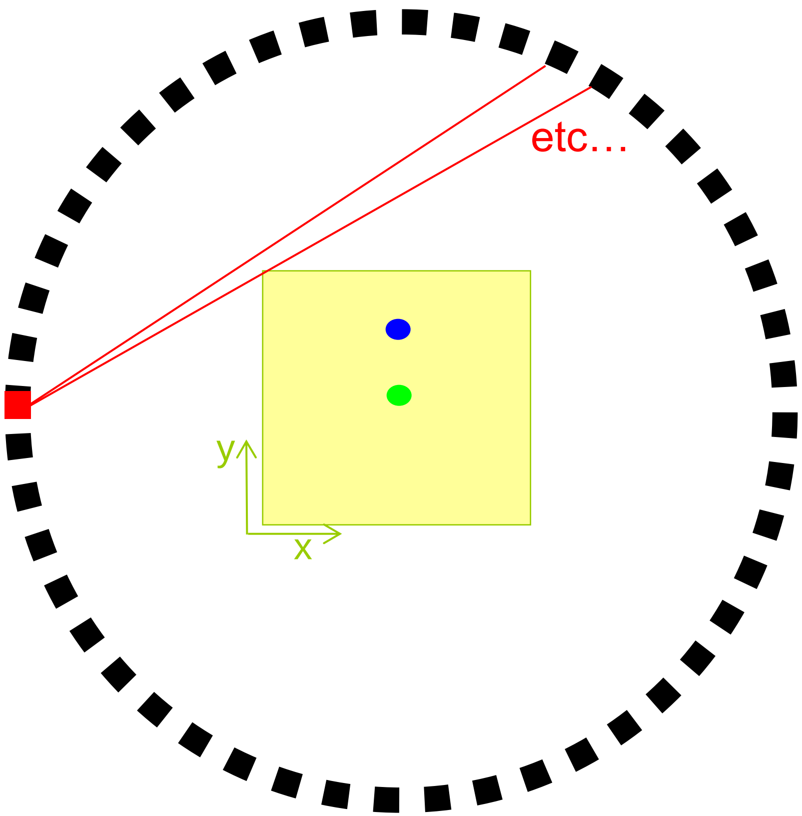
The Christie NHS
NHS Foundation Trust

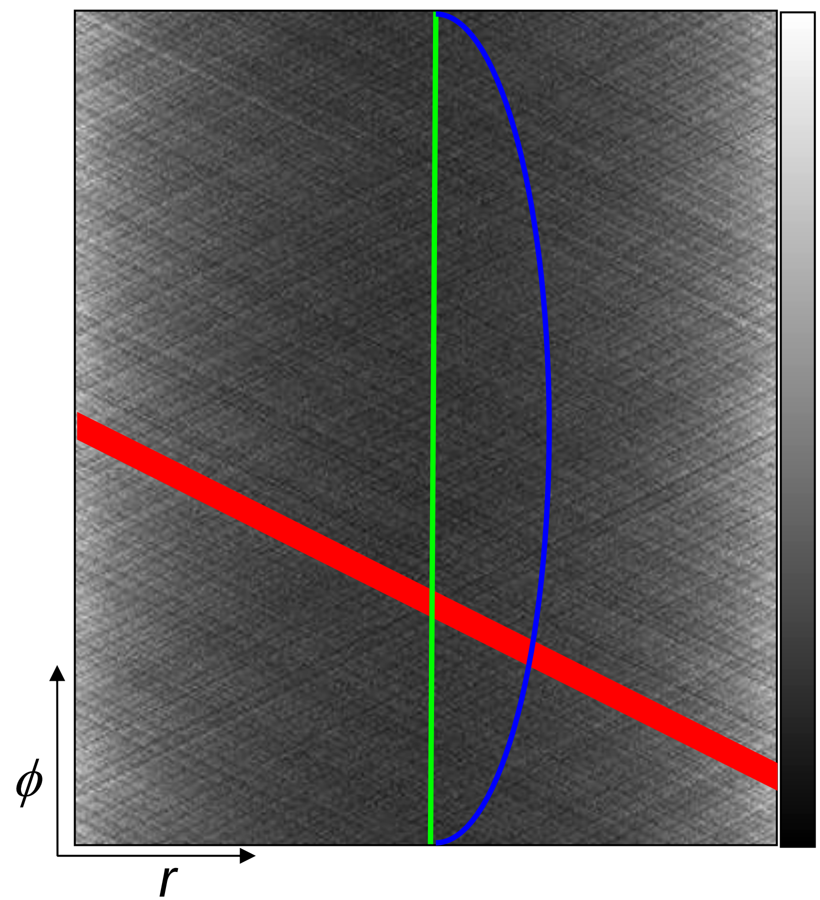
QC & Performance

- QA – Quality Assurance – The System
- QC – Quality Control – The Tests
- Validation
  - Test the system as you're going to use it!
  - e.g. Whole-Body SUV, Dynamics, Different Isotopes
- Performance Measurement, i.e. NEMA
- Image Quality Phantoms
- Significance of Errors & Examples

(PET) Sinograms

- Points in image → sine waves
- Detectors → diagonal lines





Sinograms → Fansums

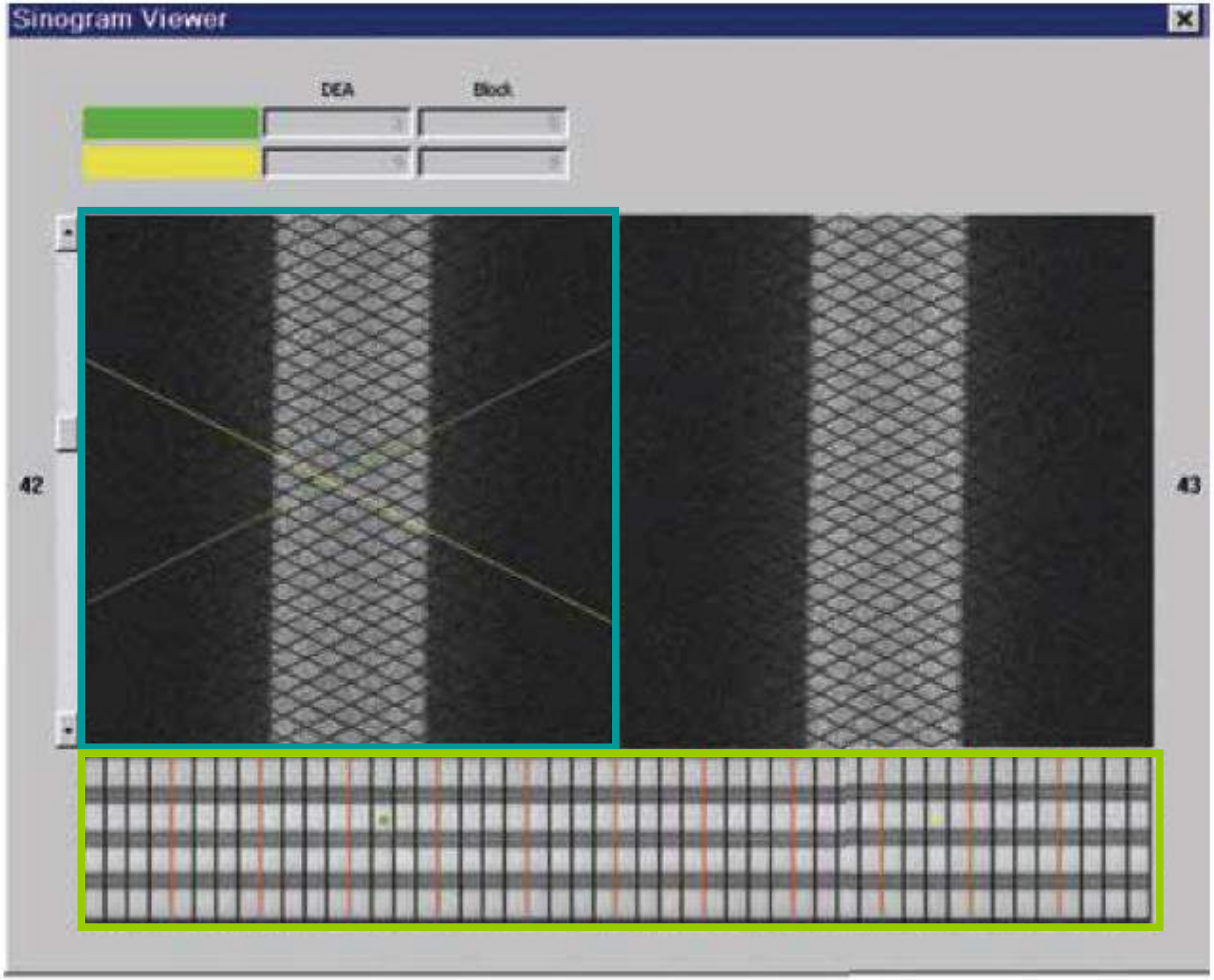
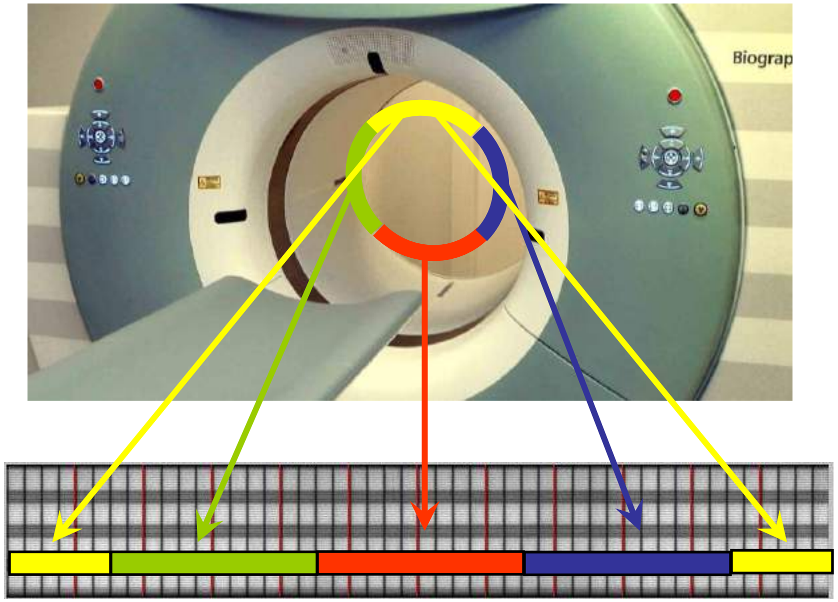


Figure 1: Daily QC sinogram and fansum images (resulting from irradiation with a ^{68}Ge cylinder in the centre of the field of view on a Siemens system)

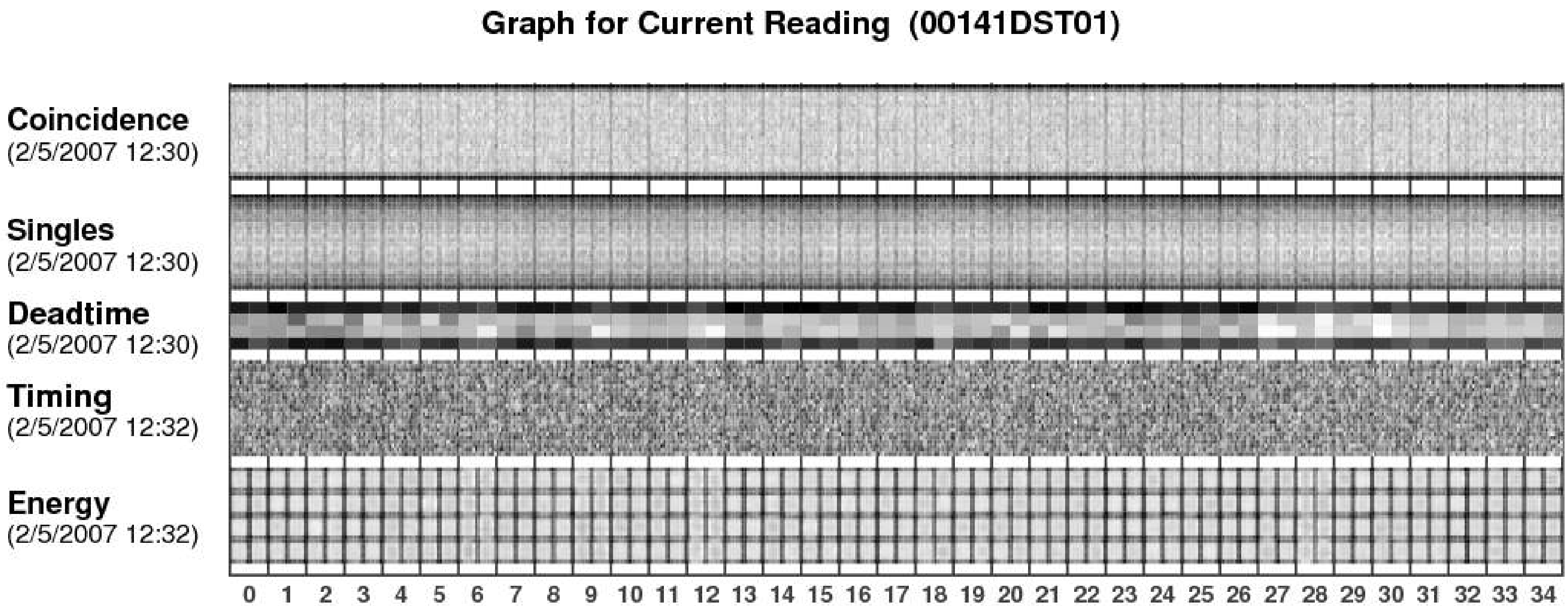
Manufacturers' PET QC

- Rotating ^{68}Ge Pin
  - e.g. GE 710
- ^{68}Ge Cylinder
  - Siemens
- ^{68}Ge Annulus
  - e.g. GE DR-MI, MI
- The future?
  - ^{176}Lu from L(Y)SO



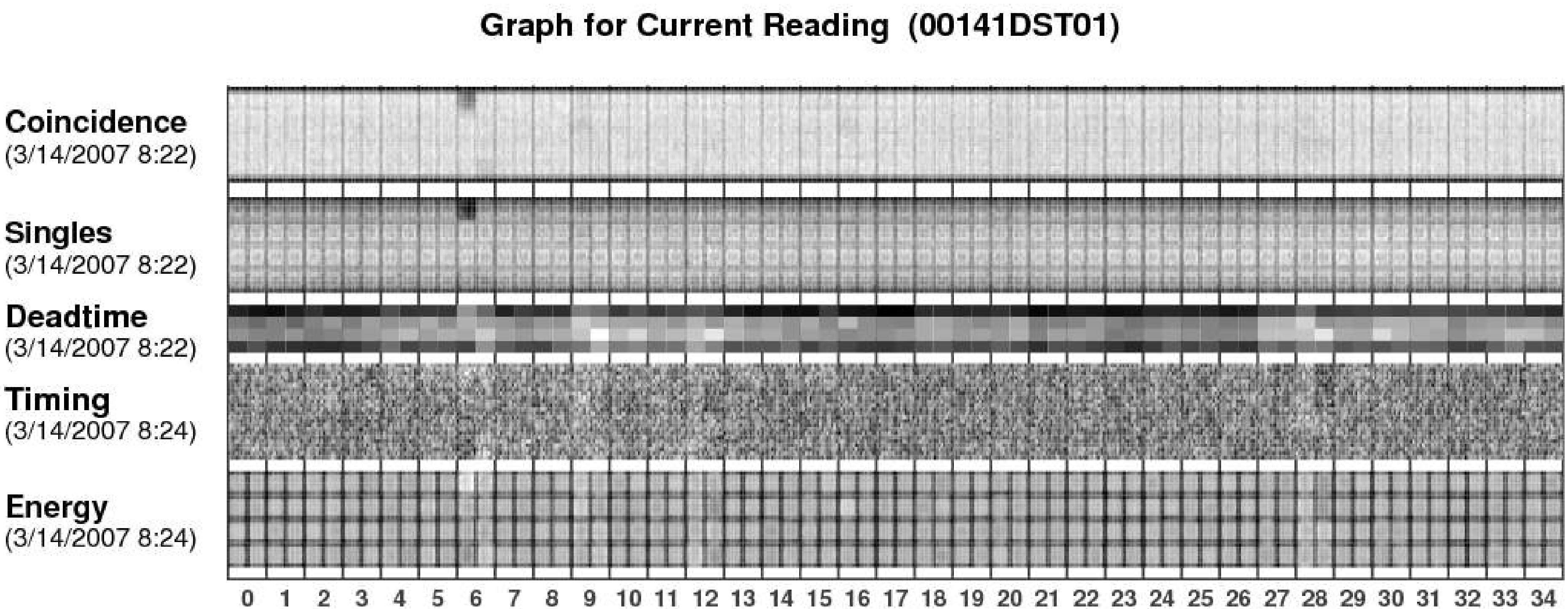
e.g. GE's Daily PET QC – "DQA"

Internal ^{68}Ge Rod Source



Item	Low Limit	High Limit	Current Reading	R/Y/G
PET Coincidence Mean	203.4177	465.4177	329.3317	Green
PET Coincidence Variance	49.02311	113.02311	79.01493	Green
PET Singles Mean	3944.3755	7740.3755	5790.274	Green
PET Singles Variance	455.21167	939.2117	685.02814	Green
PET Deadtime Mean	–0.19595	0.03405	0.00387	Green
PET Timing Mean	–0.24987	0.25013	–1.4E–4	Green
PET Energy Shift	–8.0	8.0	–1.0575492	Green

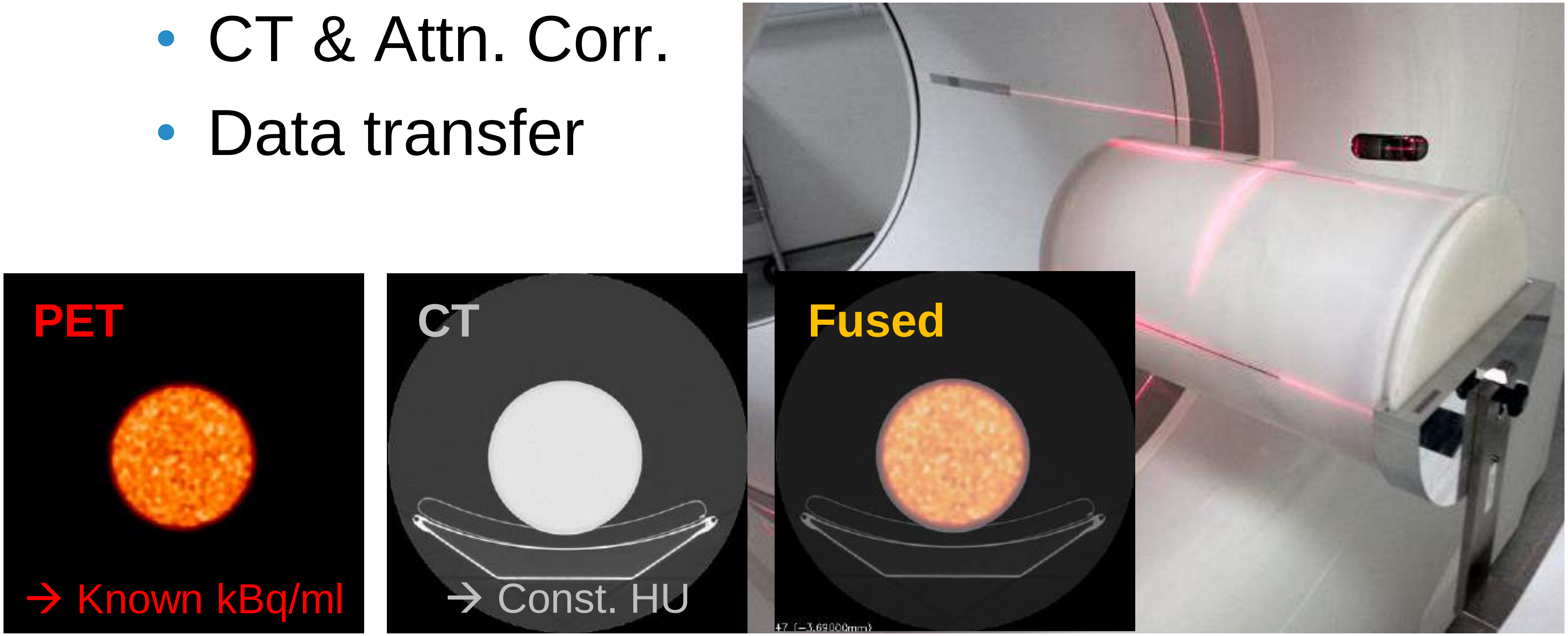
e.g. Low Block



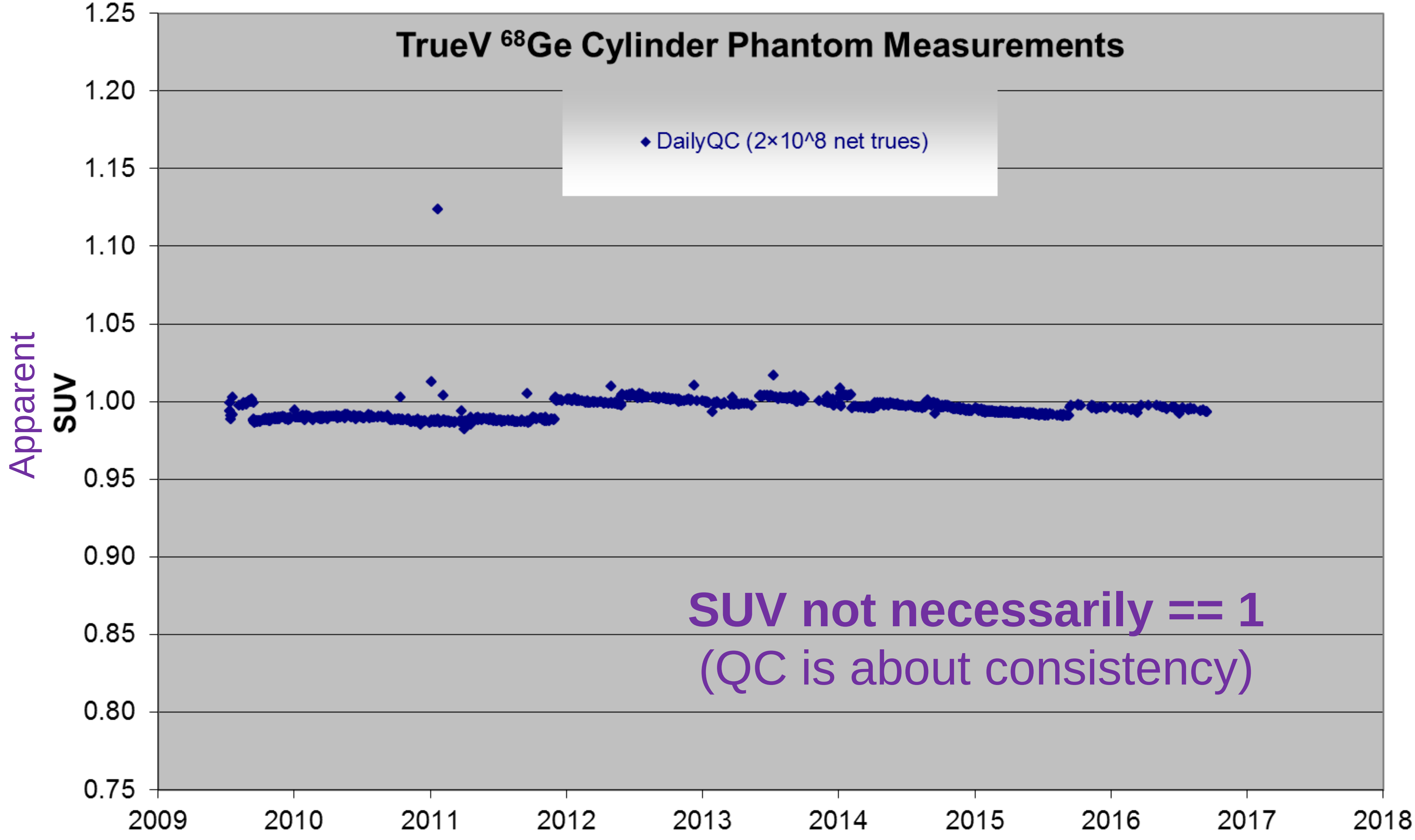
Item	Low Limit	High Limit	Current Reading	R/Y/G
PET Coincidence Mean	1101.3138	1363.3138	1226.7034	Green
PET Coincidence Variance	264.50168	328.50168	286.62927	Green
PET Singles Mean	20831.115	24627.115	23617.803	Green
PET Singles Variance	2427.3413	2911.3413	2671.6418	Green
PET Deadtime Mean	–0.18267	0.04733	0.0175	Green
PET Timing Mean	–0.25021	0.24979	0.0082	Green
PET Energy Shift	–8.0	8.0	8.023587	Yellow

QC – WB ^{68}Ge Cylinder PET-CT

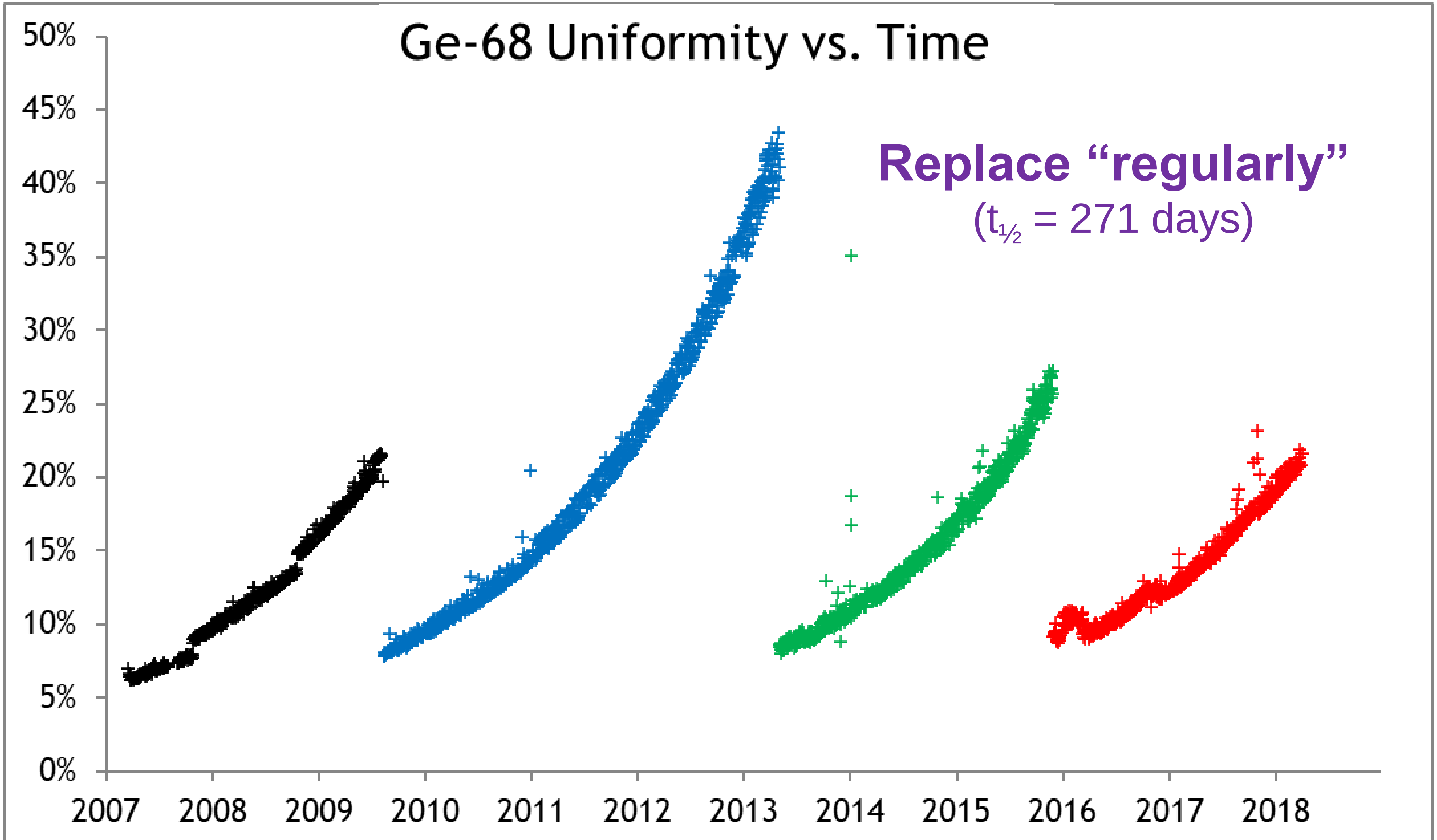
- Tests the whole process:
  - Database
  - PET inc. multi-bed, demographics
  - CT & Attn. Corr.
  - Data transfer



Long Term Trends

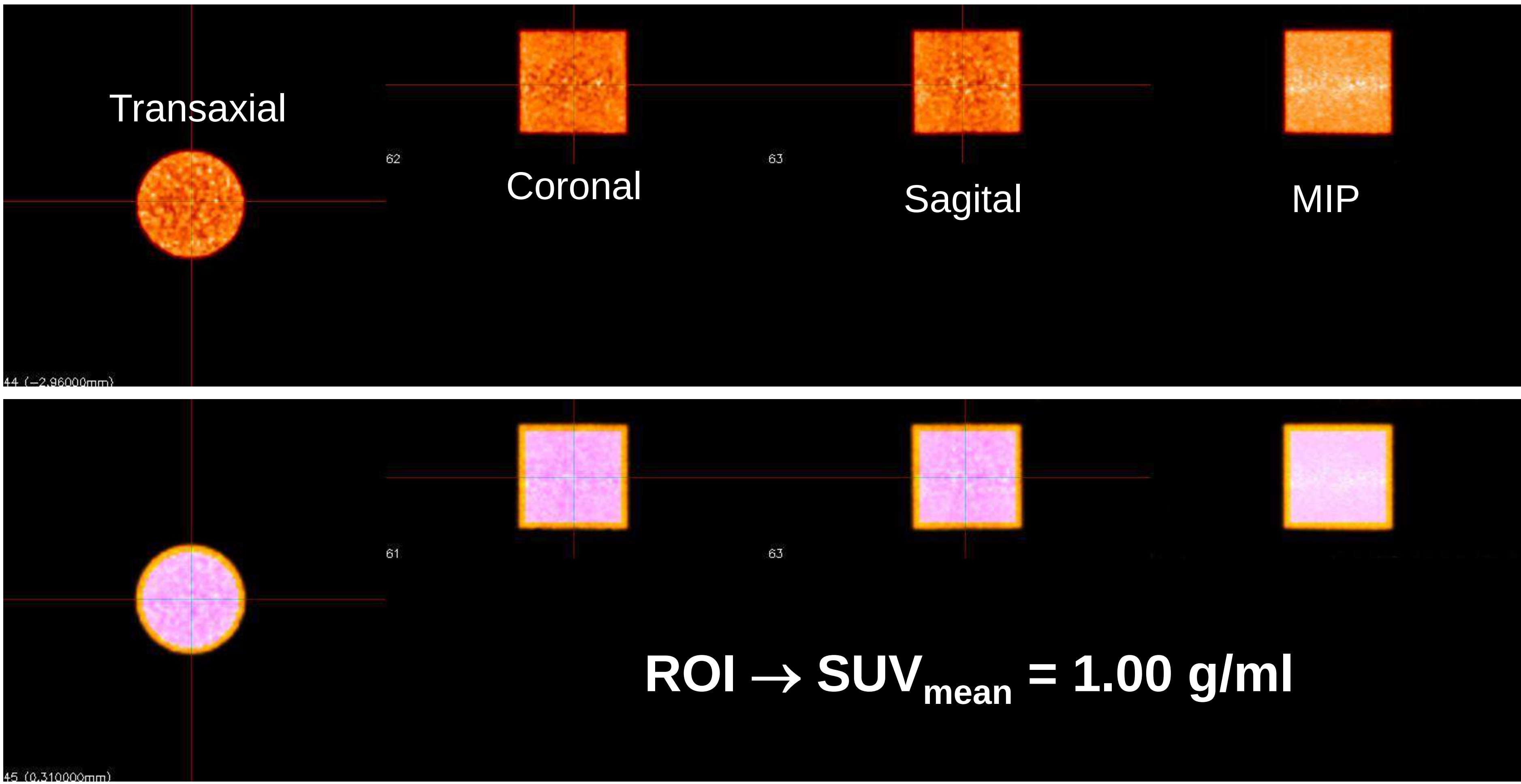


Long Term Trends



Validation – Uniform ^{18}F Cylinder

- Results, e.g. +/-10%

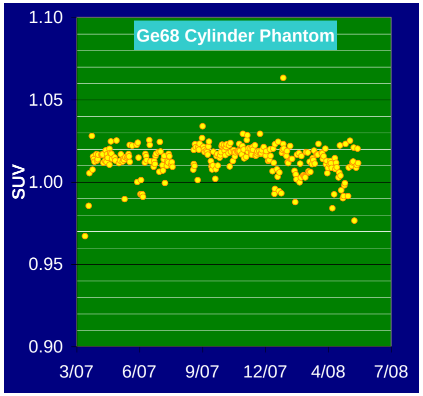


Errors in Components of SUV

- Scanner

  ~1.1%

  (daily ^{68}Ge phantom)



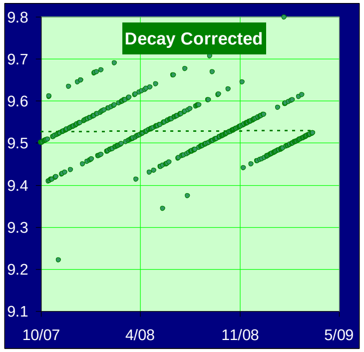
→ **1.3%**

(for EXAMPLE!)

- Dose Calibrator

  ~0.6%

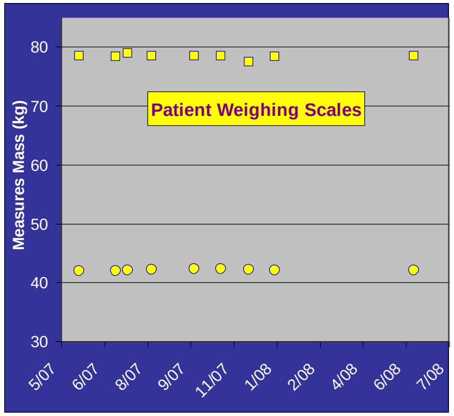
  (daily ^{137}Cs check)



- Patient Weighing Scales

  ~0.4%

  (not including effects of clothes, hydration, etc.)



Validation – Dynamics – PET-CT

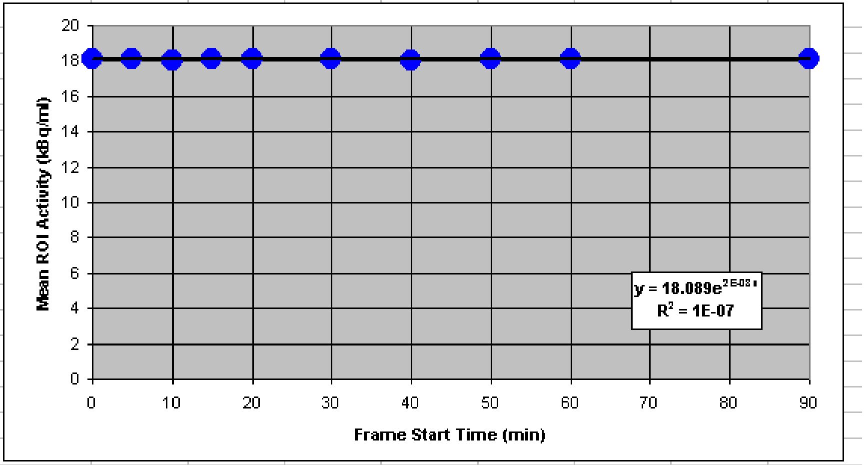
HiREZ - Validation - 29/3/07

Experiment Set-Up:	A_0 (MBq)			Reference Values:	A_0 (kBq/ml)
Whole Body	122.9	Volume (ml)	5668	WB	21.683
List Mode (LM)	100.4	$t_{½}$ (min)	109.77	LM	17.713

Image Analysis:

Whole Body	Duration (min)	Start Time (min)	mean (kBq/ml)	CoV (%) Planes	CoV (%) Radial	[additional data] uniformity (%sd/mean)
FBP	2×3	0	22.375	1.325	0.521	7.468
Iterative	2×3	0	22.306	1.334	0.438	4.617
LM-Static	**Duration (min)**	**Start Time (min)**	**mean (kBq/ml)**	**Planes**	**Radial**	**uniformity (%sd/mean)**
FBP	120	0	18.019	0.533	0.216	2.932
Iterative	120	0	17.992	0.547	0.211	1.921
LM-Dyn.-FBP	**Duration (min)**	**Start Time (min)**	**mean (kBq/ml)**	**Planes**	**Radial**	**uniformity (%sd/mean)**
1	5	0	18.111	0.768	0.438	11.085
2	5	5	18.105	0.697	0.317	11.307
3	5	10	18.019	0.768	0.438	11.085
4	5	15	18.109	0.849	0.295	11.324
5	10	20	18.108	0.588	0.354	8.303
6	10	30	18.096	0.530	0.354	8.545
7	10	40	18.073	0.597	0.575	8.602
8	10	50	18.089	0.547	0.417	8.989
9	30	60	18.087	0.523	0.336	5.589
10	30	90	18.095	0.541	0.214	5.991

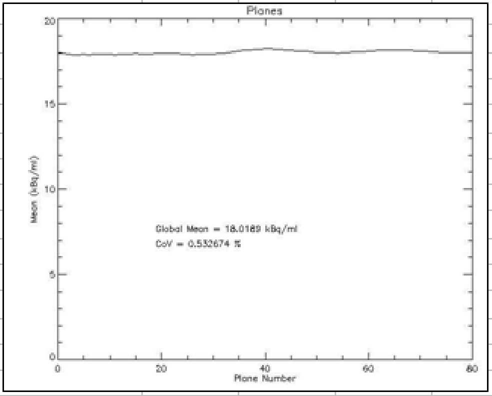
Plot of Dynamics

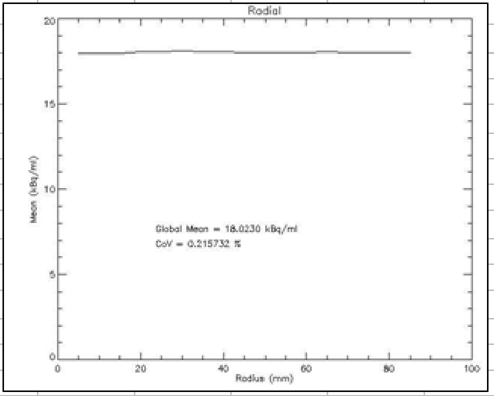


Results:

Whole Body:			Values (from above)	Error	Criteria	Validated?
	FBP	A_0	22.375	3.19%	5%	PASSED
	FBP	CoV-Planes	1.325%	-	5%	PASSED
	FBP	CoV-Radial	0.521%	-	5%	PASSED
	Iterative	A_0	22.306	2.87%	5%	PASSED
	Iterative	CoV-Planes	1.334%	-	5%	PASSED
	Iterative	CoV-Radial	0.438%	-	5%	PASSED
LM-Static:			**Values (from above)**	**Error**	**Criteria**	**Validated?**
	FBP	A_0	18.019	1.72%	5%	PASSED
	FBP	CoV-Planes	0.533%	-	5%	PASSED
	FBP	CoV-Radial	0.216%	-	5%	PASSED
	Iterative	A_0	17.992	1.57%	5%	PASSED
	Iterative	CoV-Planes	0.547%	-	5%	PASSED
	Iterative	CoV-Radial	0.211%	-	5%	PASSED
			Values (fitted)	**Error**	**Criteria**	**Validated?**
LM-Dynamic:		mean-A_0	18.089	2.12%	5%	PASSED
		CoV	0.151%	-	5%	PASSED

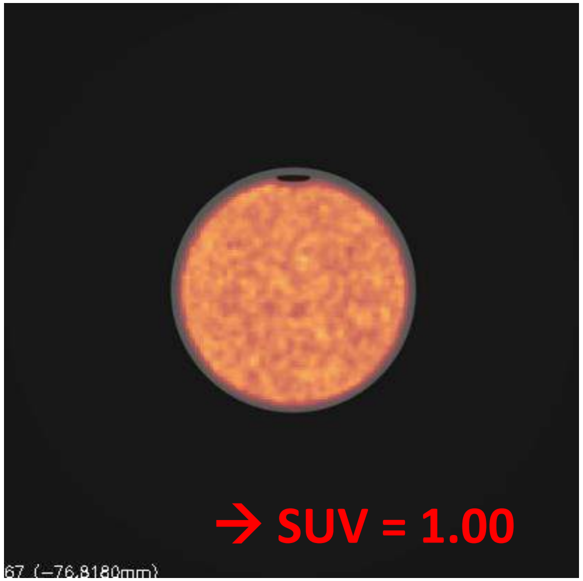
Plots of Axial and Radial Variations (from LM-Static FBP)



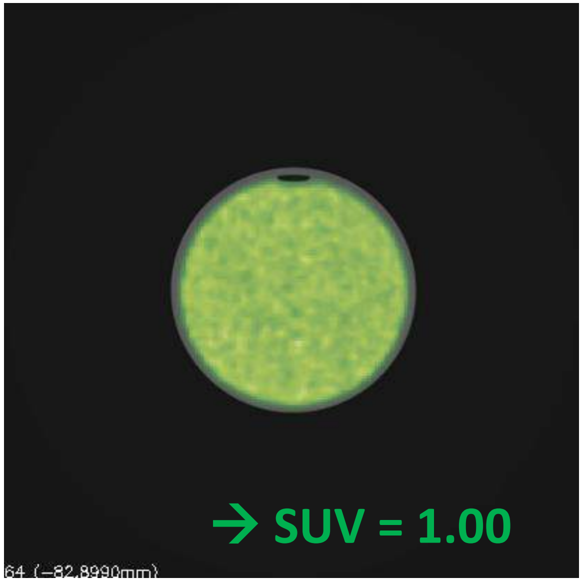


Validation – Isotopes

^{18}F



^{68}Ga



- **Different positron abundances and half-lives**

Performance Measures – Why?

- Objectively measure scanner performance
  - *So?!*
- Comparison to manufacturer specification
  - Did we get what we ordered?
- Comparison to other systems
  - Is it any good?
- Establish a baseline
  - Is it's performance stable?

...Give physicists something to do!

Leicester – Nov’2017

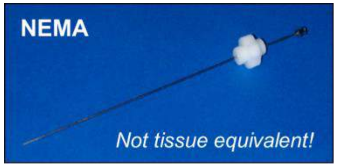
The Christie NHS
NHS Foundation Trust

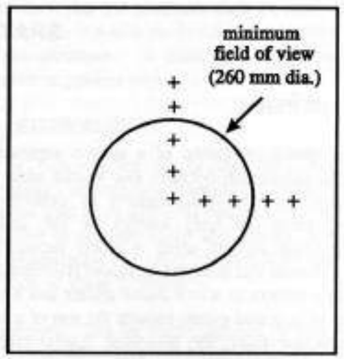
A Brief History of NEMA NU 2

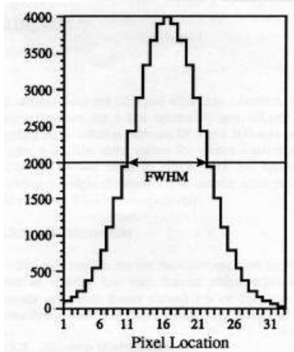
- 1994, 2001, 2007, 2012, 2018…

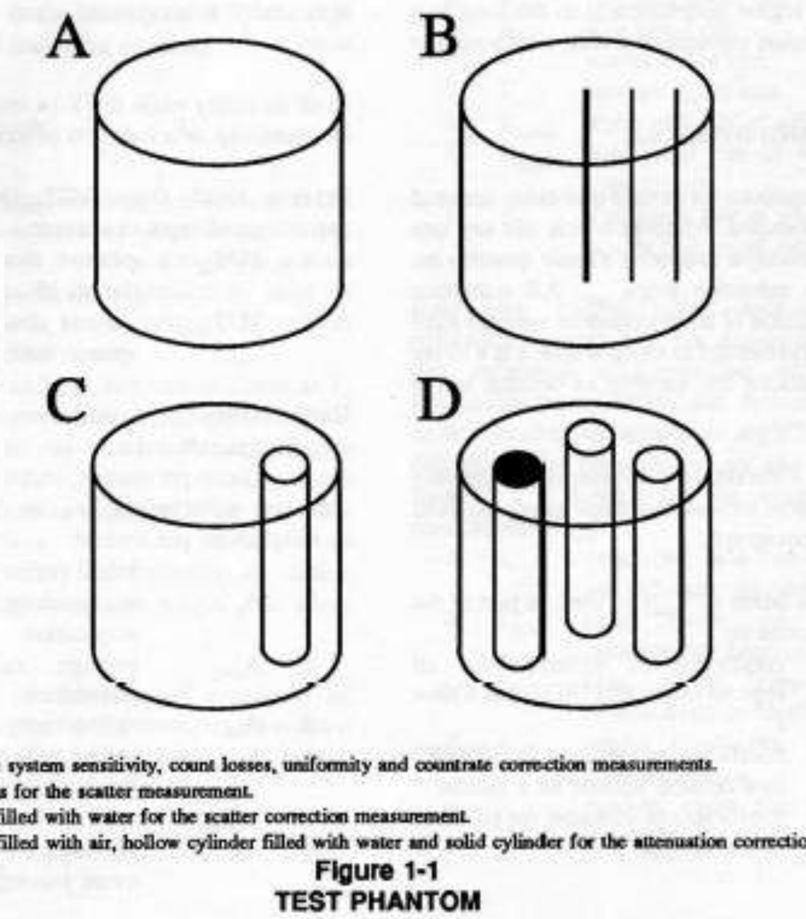
NEMA NU 2 – 1994

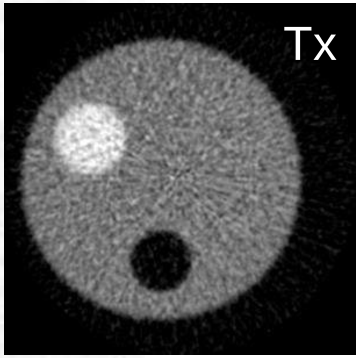
- Karp et al 1991 JNM 32(12) 2342

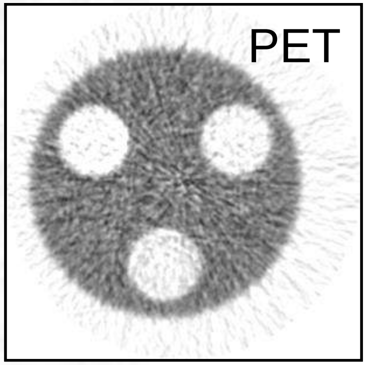












NEMA NU 2 – 2001

- Daube-Witherspoon et al 2002 JNM **<u>43(10)</u>** 1398

e.g….

Absolute Sensitivity

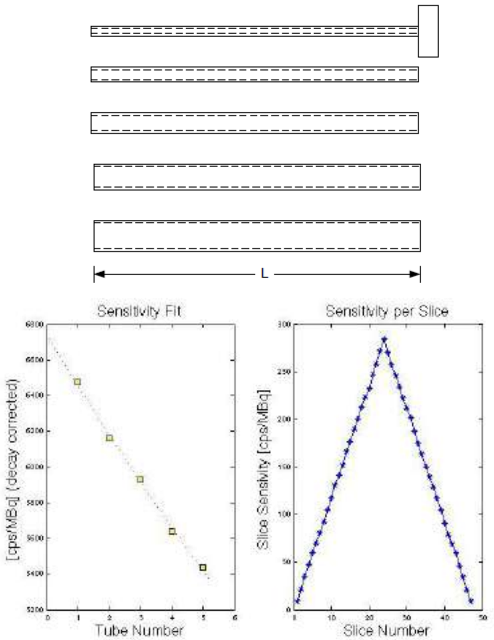
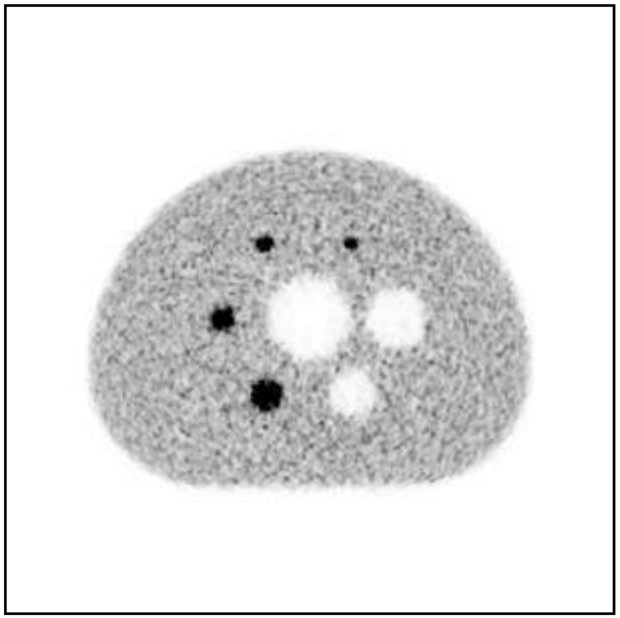


Image Quality



NEMA NU 2

2007

- Intrinsic activity of ^{176}Lu in L(Y)SO
- Watson et al 2004 JNM <u>45(5)</u> 822-826

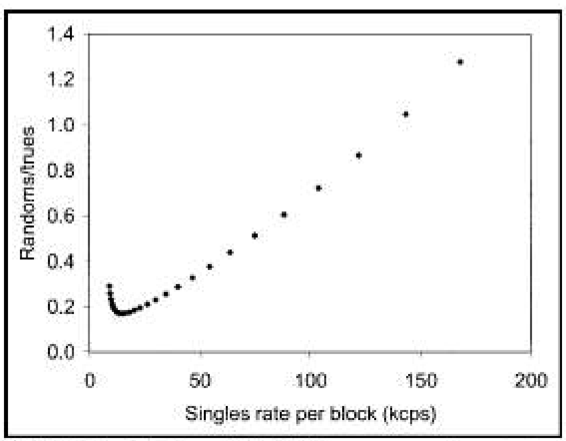


FIGURE 1. RTR for a NEMA NU 2-2001 counting-rate test performed on an ACCEL, as a function of the average singles rate in a block detector.

2012

- Resolution out to 20 cm

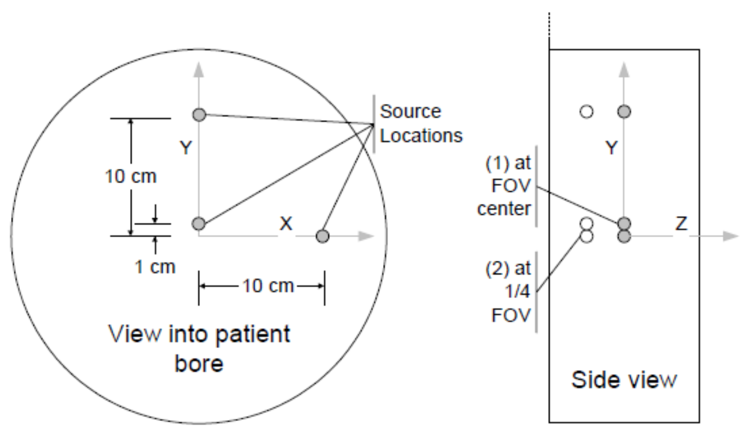
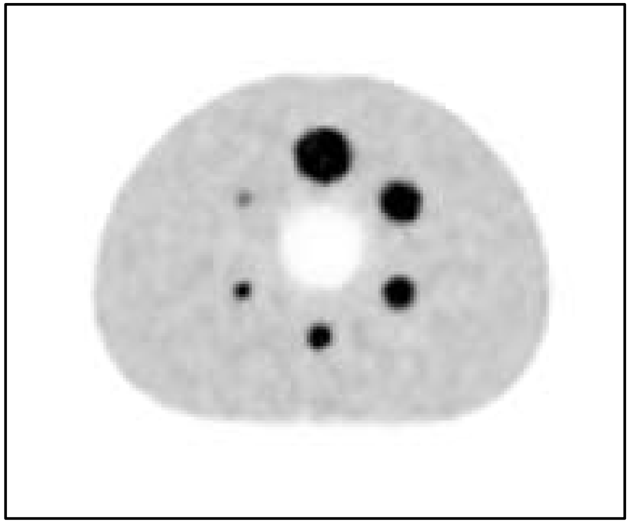
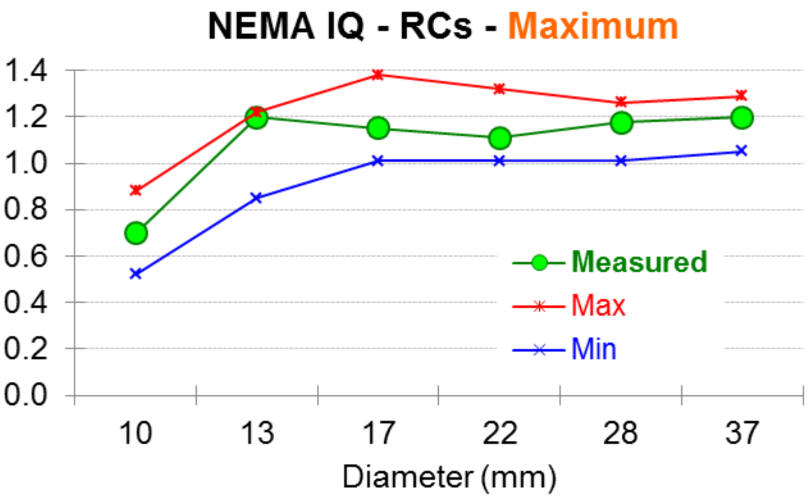


Figure 3-1
POSITIONS OF SOURCE FOR RESOLUTION MEASUREMENT

NEMA NU 2 2018 – Modifications

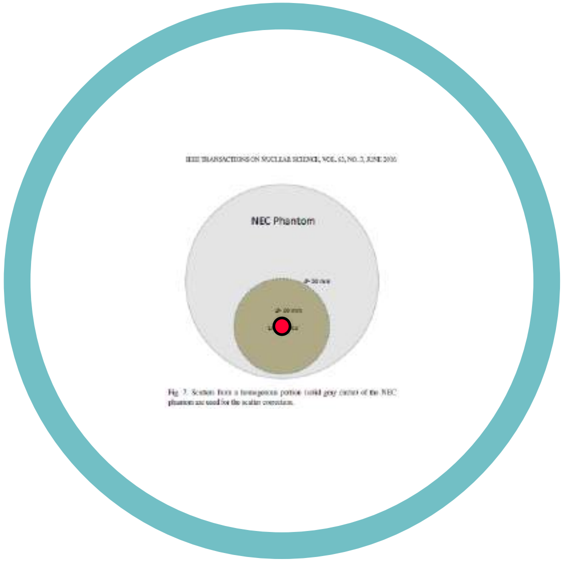
- Spatial Resolution – ^{22}Na as well as ^{18}F
- Scatter & Count-Rate – Positioning…
- Accuracy – Analysis of 80% of slices
- **Image Quality – ALL spheres hot at 4:1 only**

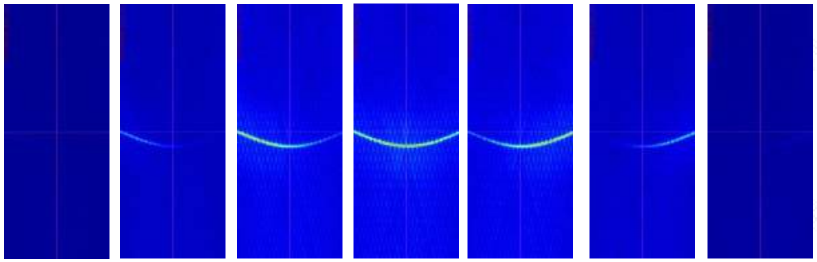




NEMA NU 2 2018 – New Tests 1

- Time-of-Flight Resolution
  - Dependent on source distribution
  - Uses count-rate data





ToF sinogram timing bins

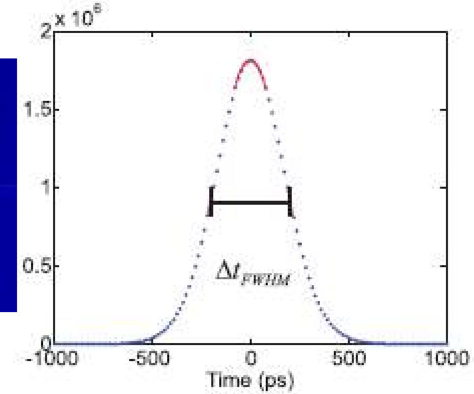


Fig. 9. An example timing histogram. A parabolic fit is applied to the peak to obtain the maximum value of the distribution, then the FWHM is found by applying two linear fits at the regions around the half-maximum value.

- Wang et al 2016 IE3-NS 63(3) 1335

NEMA NU 2 2018 – New Tests 2

- PET-CT Coregistration Accuracy

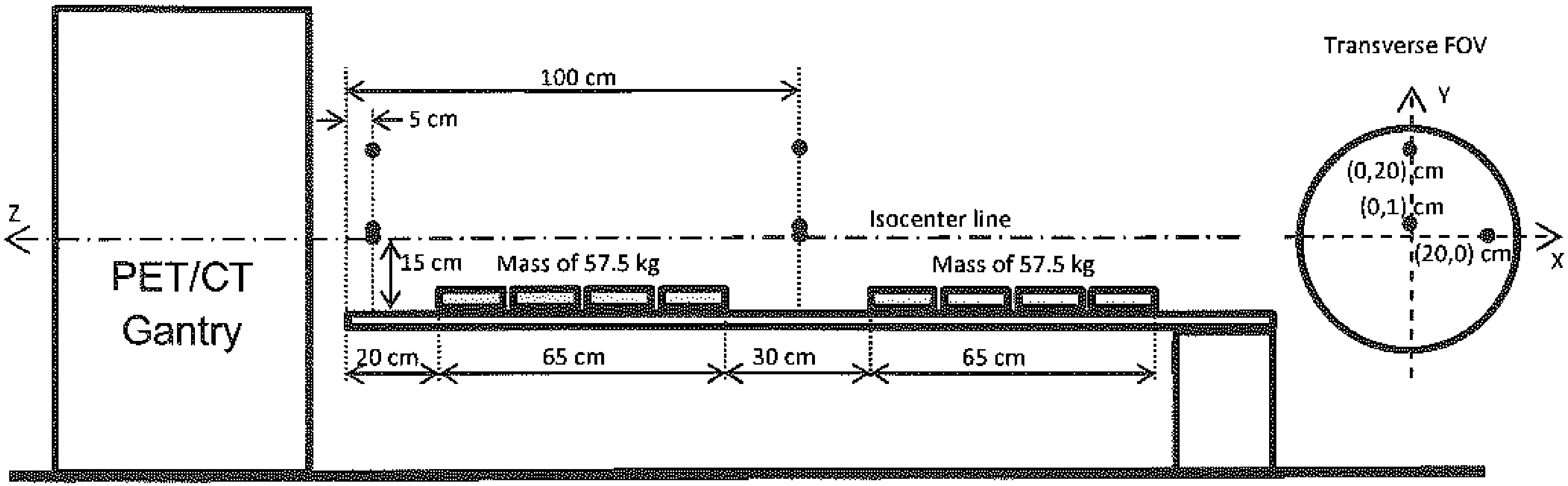


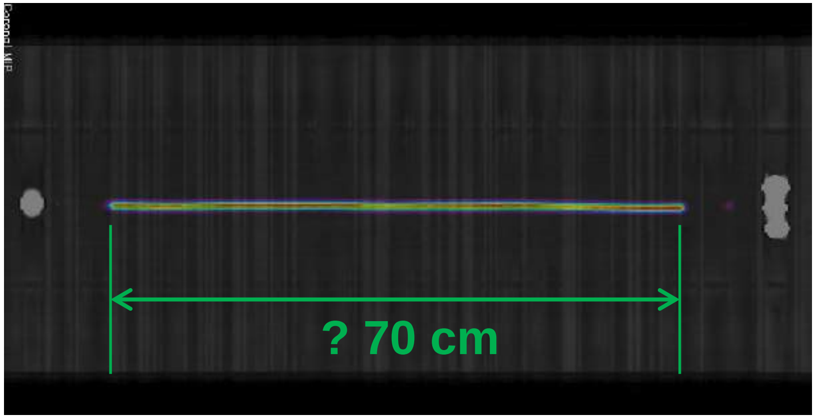
Figure 9-1
Position of Fiducial Markers and Masses on the Patient Table

NEMA NU 2 – Sensitivity

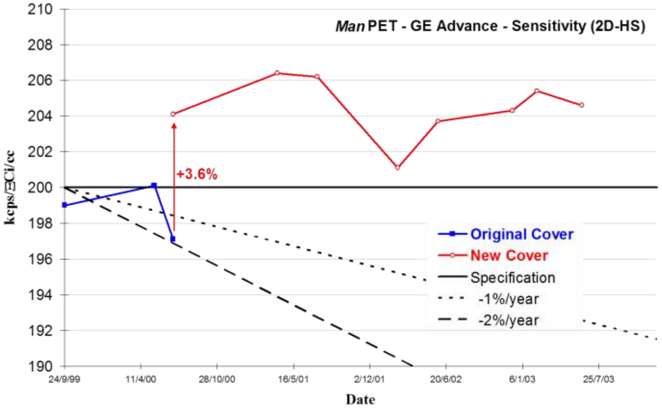
≥2001

- A test of how well you can fill the line!

→ Do WB PET-CT?



cf. 1994



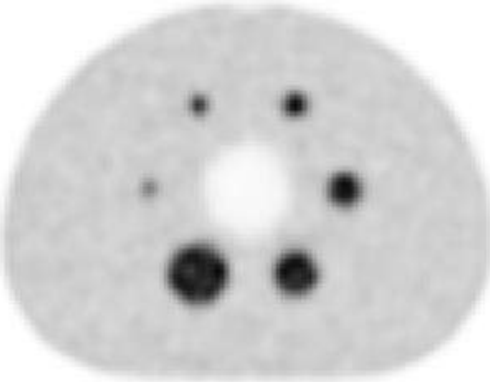
NB: Pass/fail criteria should allow for your dose calibrator being slightly (<5%) off.

NEMA Testing …And Finally

- Phantom **“kit”**
  - *Beg, borrow or steal…*
  - **Buy Image Quality**
- Specify details in tender:
  - Inc. software (? version)
    & assistance from manufacturer
- Do hand-in-hand with manufacturer
  & ask a friend for help if needed!

Image Quality Phantoms

- Overall assessment of image quality
- VERY useful for testing system changes
- Also for testing data transmission procedures:
  - DICOM format
  - Anonymisation
  - ftp/CD writing, etc.



- May be required for entry into clinical trial

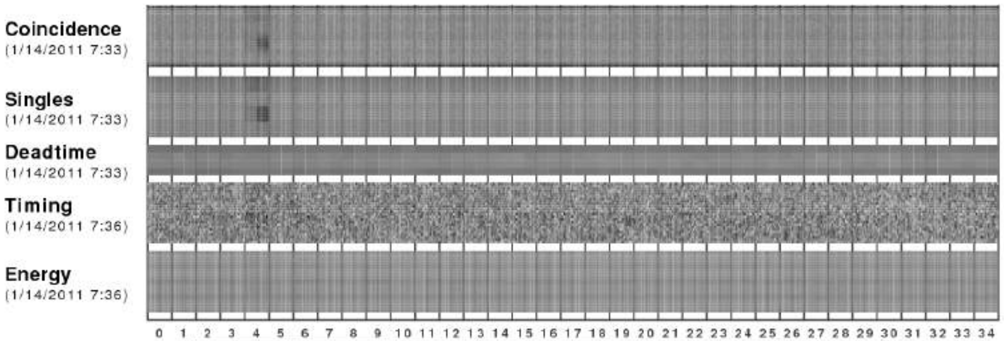
→ **DAY TWO**

PET in the context of multi-centre trials
Lucy Pike, Kings College London

How Significant Are QC Errors? 1

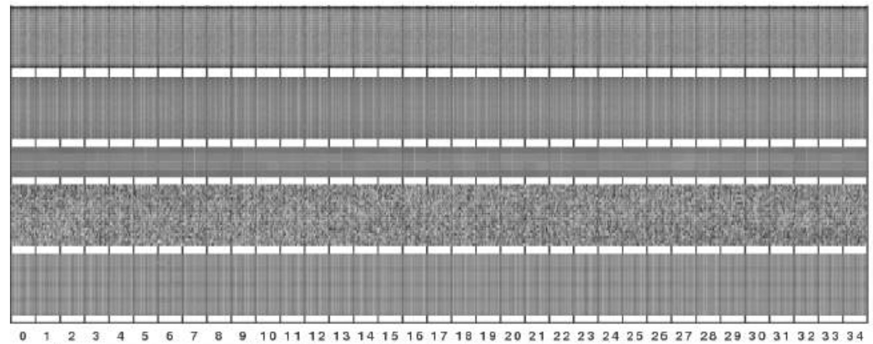
GE DSTE8 – Block Error

- Daily QC → Tune → Repeat



Item	Low Limit	High Limit	Previous Reading	R/Y/G
PET Coincidence Mean	240.91177	271.66644	243.1808	Green
PET Coincidence Variance	55.90793	63.04511	57.41297	Green
PET Singles Mean	4179.026	4712.5186	4256.124	Green
PET Singles Variance	495.2568	558.4811	565.0335	Yellow
PET Deadtime Mean	2.0E-5	0.03326	0.00324	Green
PET Timing Mean	-0.06168	0.058319997	-0.0055	Green
PET Energy Shift	-8.0	8.0	-3.6697178	Green

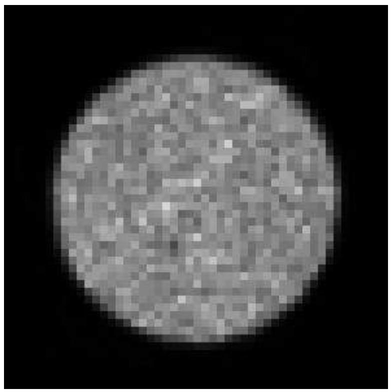
Source Pin Count Rate Mean	Source Pin Count Rate Variance	Minimum Rate	Source Pin Life	Source Pin Status
5791.042	393.23245	4500.0	98 Days	Green



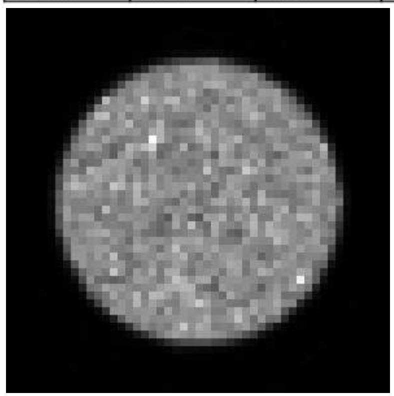
Item	Low Limit	High Limit	Current Reading	R/Y/G
PET Coincidence Mean	240.91177	271.66644	256.28912	Green
PET Coincidence Variance	55.90793	63.04511	59.47652	Green
PET Singles Mean	4179.026	4712.5186	4445.7725	Green
PET Singles Variance	495.2568	558.4811	526.86896	Green
PET Deadtime Mean	2.0E-5	0.03326	0.00326	Green
PET Timing Mean	-0.06168	0.058319997	-0.00168	Green
PET Energy Shift	-8.0	8.0	0.0	Green

Source Pin Count Rate Mean	Source Pin Count Rate Variance	Minimum Rate	Source Pin Life	Source Pin Status
5806.6943	391.68405	4500.0	99 Days	Green

^{68}Ge Phantom Std. WB PET-CT Scan



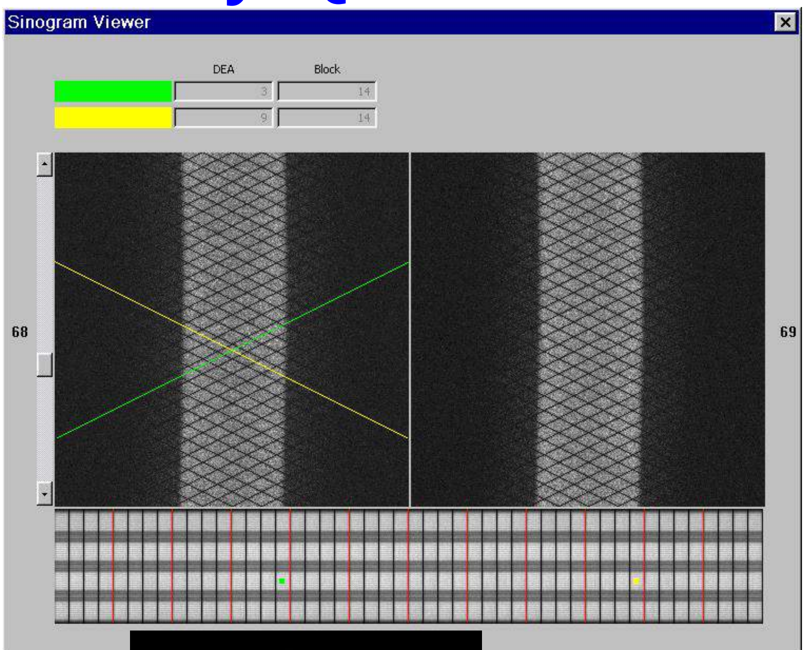
Uniformity
CoV (sd/mean)
14.55%



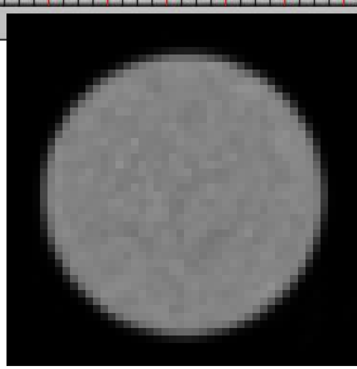
Uniformity
CoV (sd/mean)
14.30%

How Significant Are QC Errors? 2
Siemens TrueV – DEA Board Error

- Daily QC

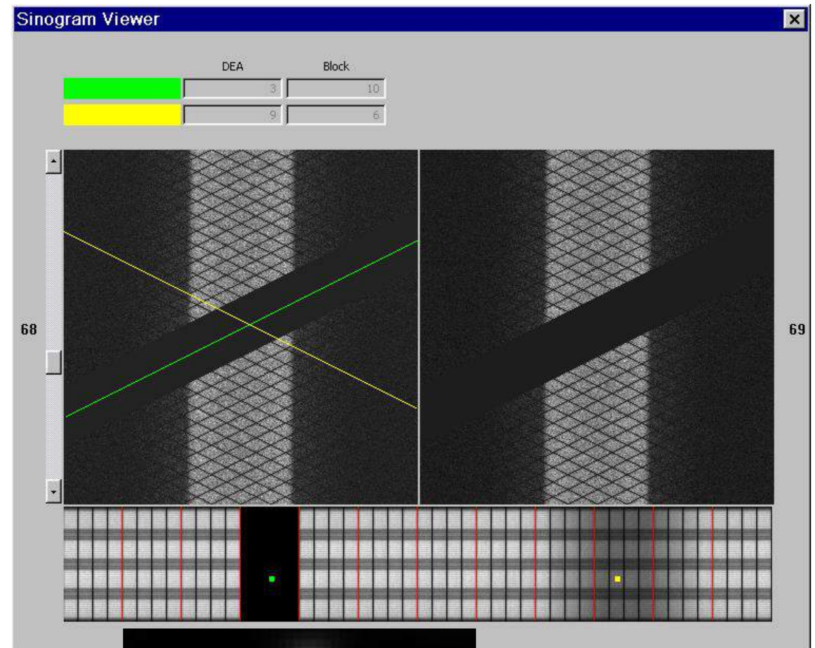


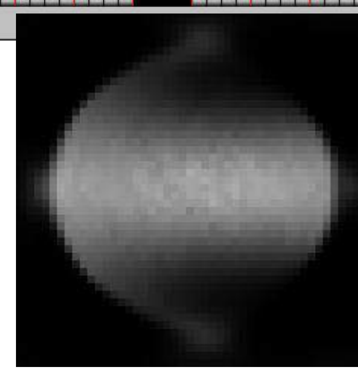
^{68}Ge Phantom Std. QC PET-CT Scan



Uniformity
CoV (sd/mean)
6.2%

- Error



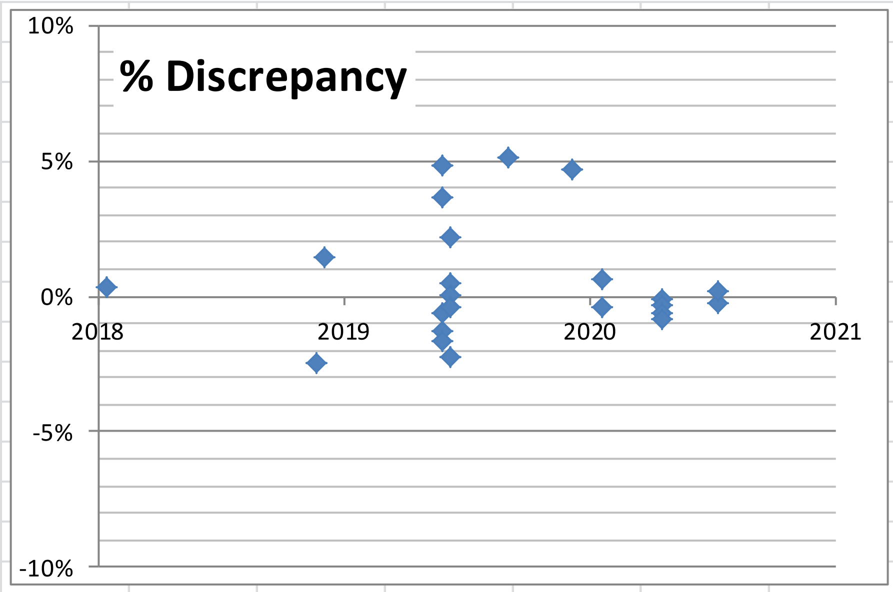


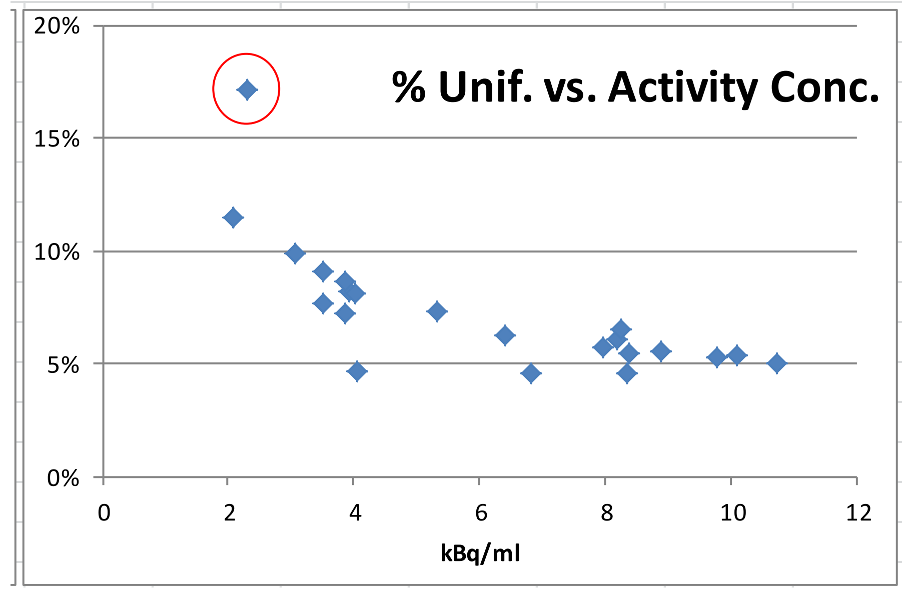
Uniformity
CoV (sd/mean)
50.6%

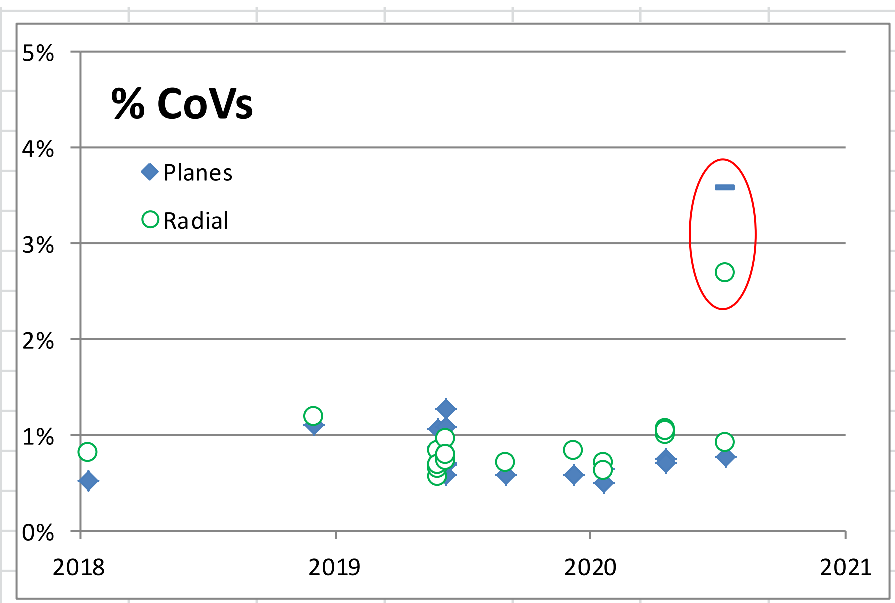
Example – SUV Check / Validation

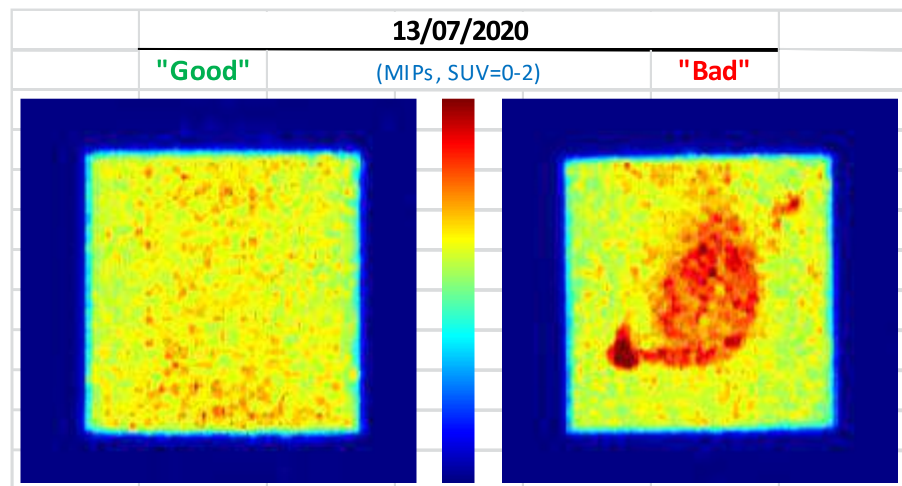
- Routine check (~every $^{3}/_{12}$)
- ~6 litre cylinder
- ~20 MBq *spare* ^{18}F
- Standard acquisition
- …
- What could possibly go wrong…?

SUV Check – Mixing









The Christie NHS
NHS Foundation Trust

QA/QC – What Else?

- 101 other things!
  - Clock time on computers
  - etc.

- Also:
  - Tracer QA/QC
  - Patient preparation →

DAY TWO

Clinical imaging protocols: Oncology
Andy Harris, The Christie NHS Foundation Trust

Clinical imaging protocols: Infection and Inflammation
Matt Memmott, Manchester University NHS Foundation Trust

Clinical imaging protocols: Cardiac Imaging
Ian Armstrong, Manchester University NHS Foundation Trust

Clinical imaging protocols: Neuroimaging
Matt Memmott, Manchester University NHS Foundation Trust

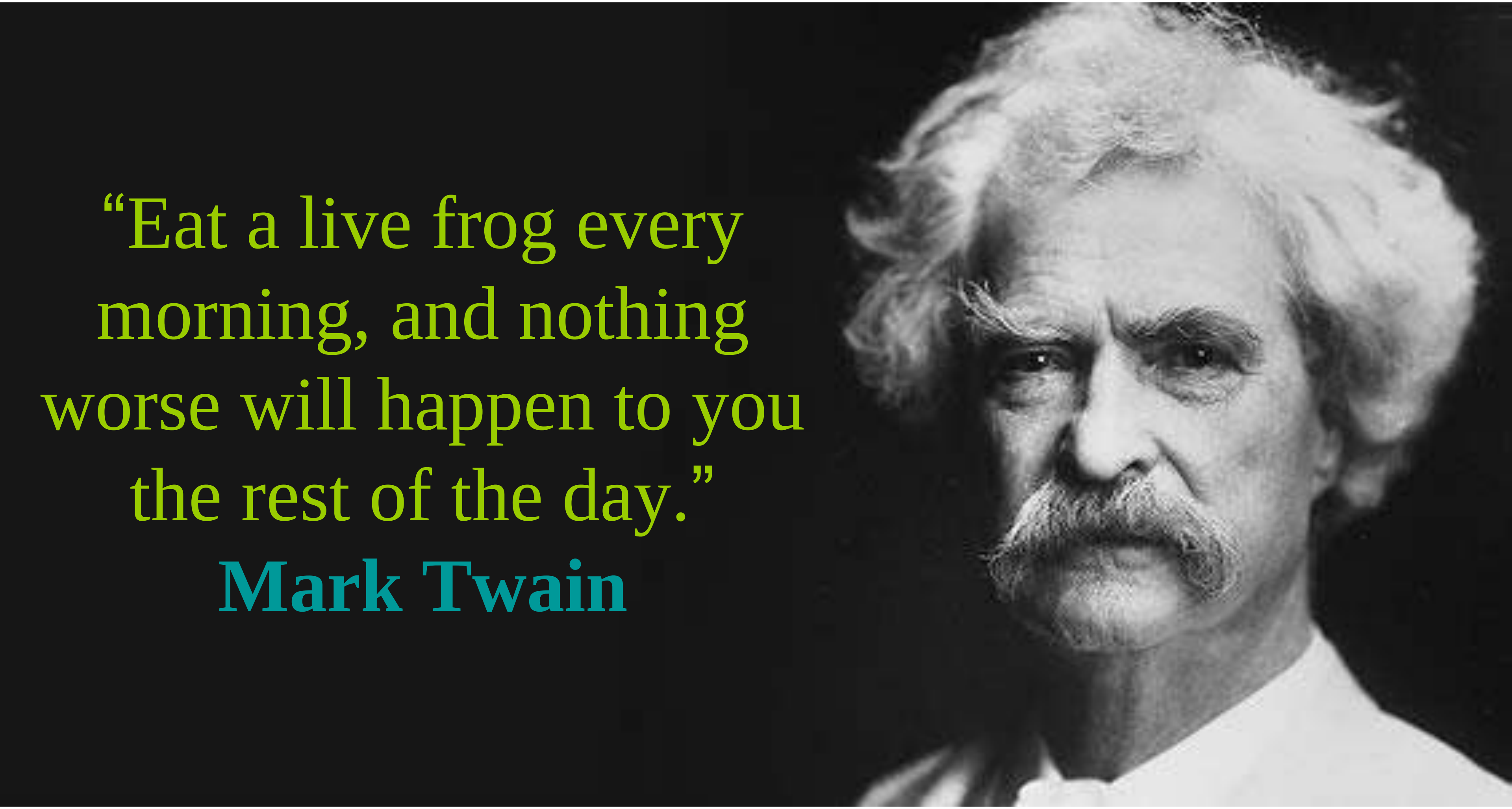
References & Further Reading

<u>QA/QC</u>

- Julyan P. Quality Assurance and Quality Control for PET-CT. In: Principles and Practice of PET/CT – Part 1 – A Technologist's Guide (EANM, Vienna) 2010 ISBN: 978-3-902785-00-8 [Free download from www.eanm.org]
- **Pike L, Julyan P, Marsden P and Waddington W. Quality Assurance of PET and PET/CT Systems. (Report 108, Institute of Physics and Engineering in Medicine, York) 2013 ISBN: 978 1 903613 54 2**
- NEMA Standards Publication NU 2-2018. Performance Measurements of PET.

The Christie NHS
NHS Foundation Trust

Is It Worth Doing “Complex” QA/QC?



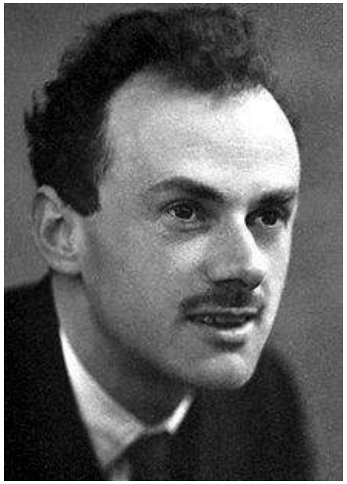
The Christie NHS Foundation Trust

An introduction to PET Physics

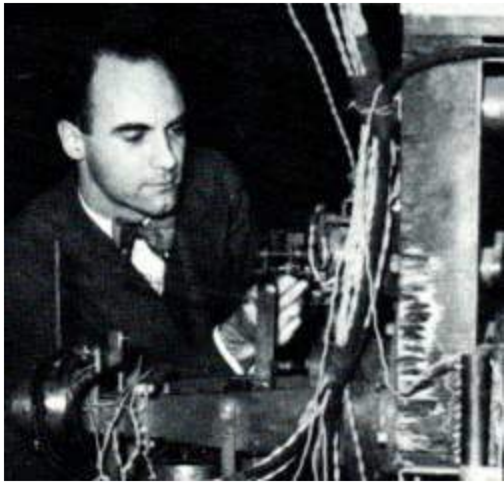
Dr Heather Williams
Consultant Medical Physicist
Group Leader for Nuclear Medicine
The Christie
Heather.Williams34@nhs.net

$$\left(\beta mc^2 + c(\alpha_1 p_1 + \alpha_2 p_2 + \alpha_3 p_3)\right)\psi(x,t) = i\hbar\frac{\partial\psi(x,t)}{\partial t}$$

Dirac wave equation

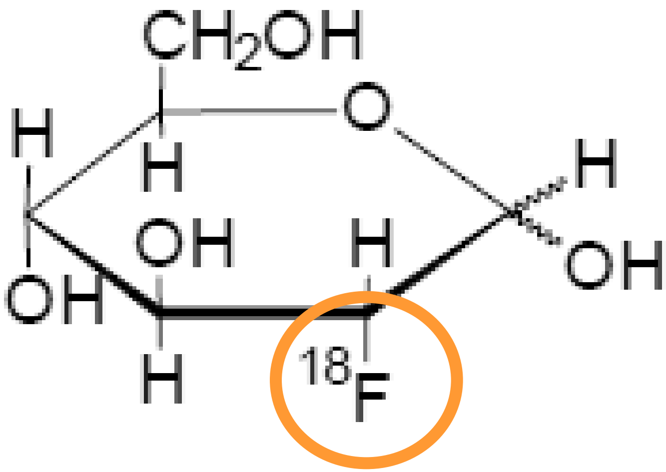


Paul Dirac
1902 – 1984
predicted the positron: 1928



Carl Anderson
1905 – 1991
discovered the positron: 1932

Nobel prize: 1936



$p \rightarrow n + e^{+}$

$e^{+} \equiv \beta^{+}$

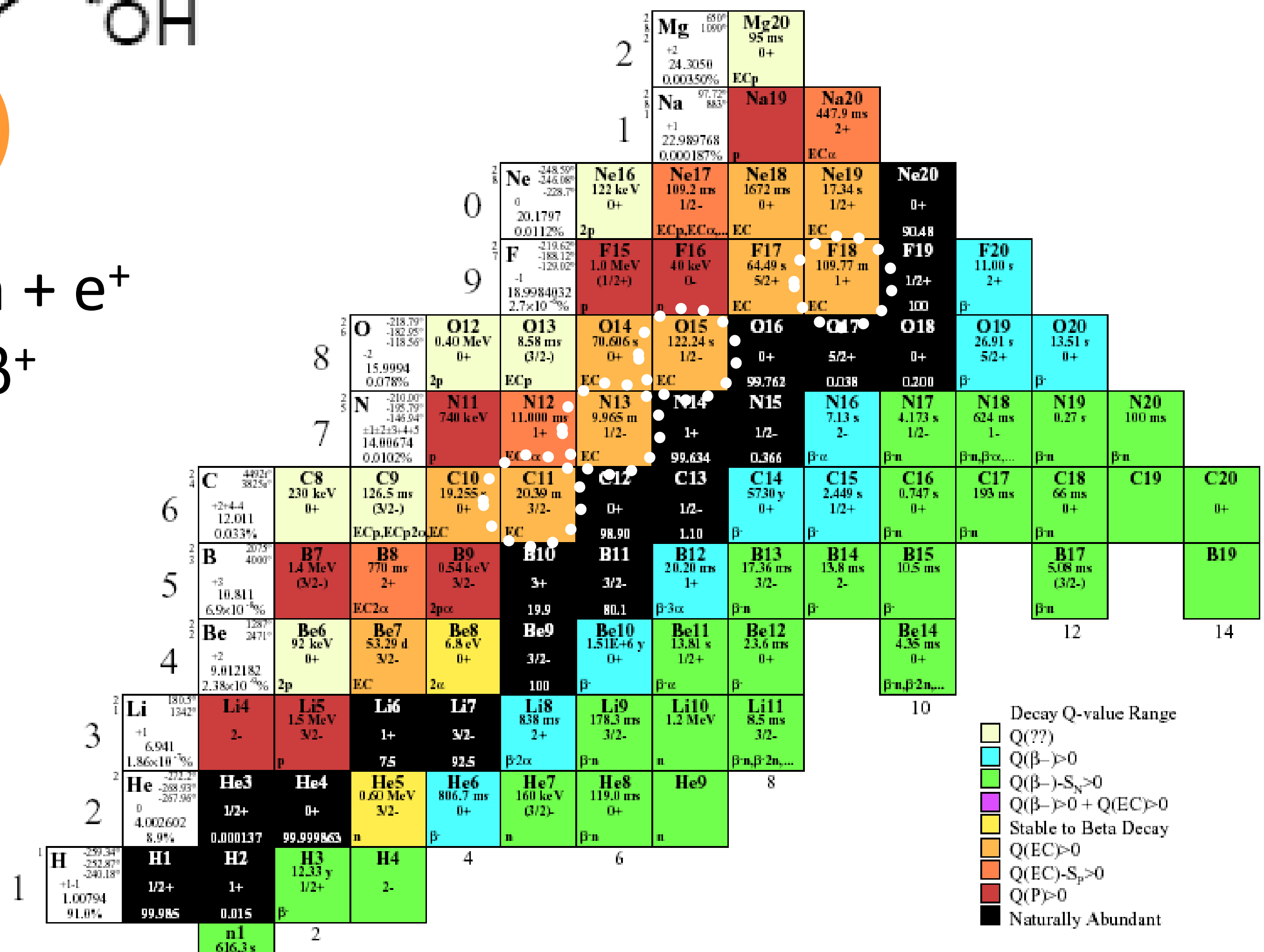


Table of the Isotopes

Properties of Positron Emitters

Pure positron emitters

Isotope	Half-life	Branching (β^+) in %	E_{max} (MeV)	E_{mean} (MeV)	R_{max} (mm)	R_{mean} (mm)
^{11}C	20.4 min	99.8	0.960	0.386	4.2	1.2
^{13}N	10.0 min	99.8	1.199	0.492	5.5	1.8
^{15}O	2 min	99.9	1.732	0.735	8.4	3.0
^{18}F	110 min	96.9	0.634	0.250	2.4	0.6
^{64}Cu	12.7 h	17.5	0.653	0.278	2.5	0.7
^{89}Zr	78.4 h	22.7	0.902	0.396	3.8	1.3

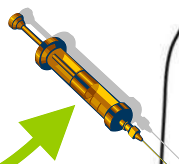
Positron emitters with prompt gammas

Isotope	Half-life	Branching (β^+) in %	β^+ E_{max} (MeV)	Branching (γ) in %	γ E (PG) (MeV)
^{68}Ga	67.8 min	87.7, 1.2	1.899, 0.821	3.2	1.077
^{76}Br	16.2 h	25.8, 6.3	3.382, 0.871	74.0, 15.9	0.559, 0.657
^{82}Rb	1.3 min	81.8, 13.1	3.378, 2.601	15.1	0.777
^{86}Y	14.7 h	11.9, 5.6	1.221, 1.545	82.5, 32.6	1.077, 0.627
^{124}I	100.2 h	11.7, 10.7	1.535, 2.138	62.9, 11.2	0.602, 1.691

Conti and Eriksson, EJNMMI Physics 2016, 3: 8.

Nuclear Medicine Imaging

1. Make slightly radioactive tracer



2. Give tracer to patient, normally by injection

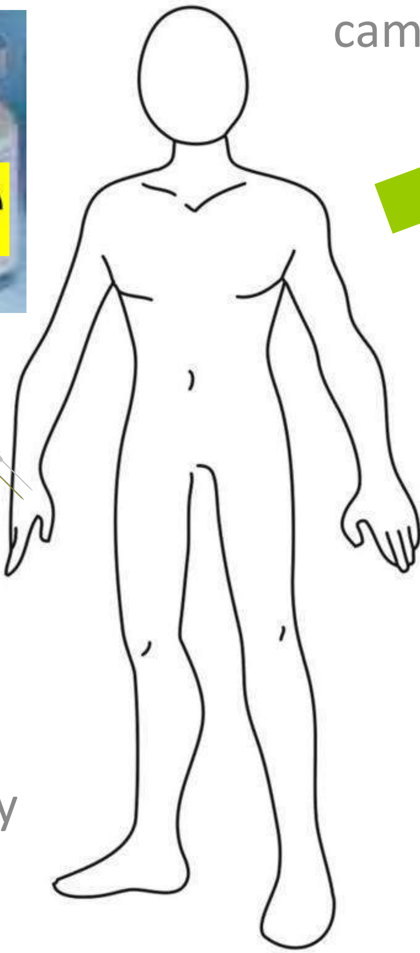
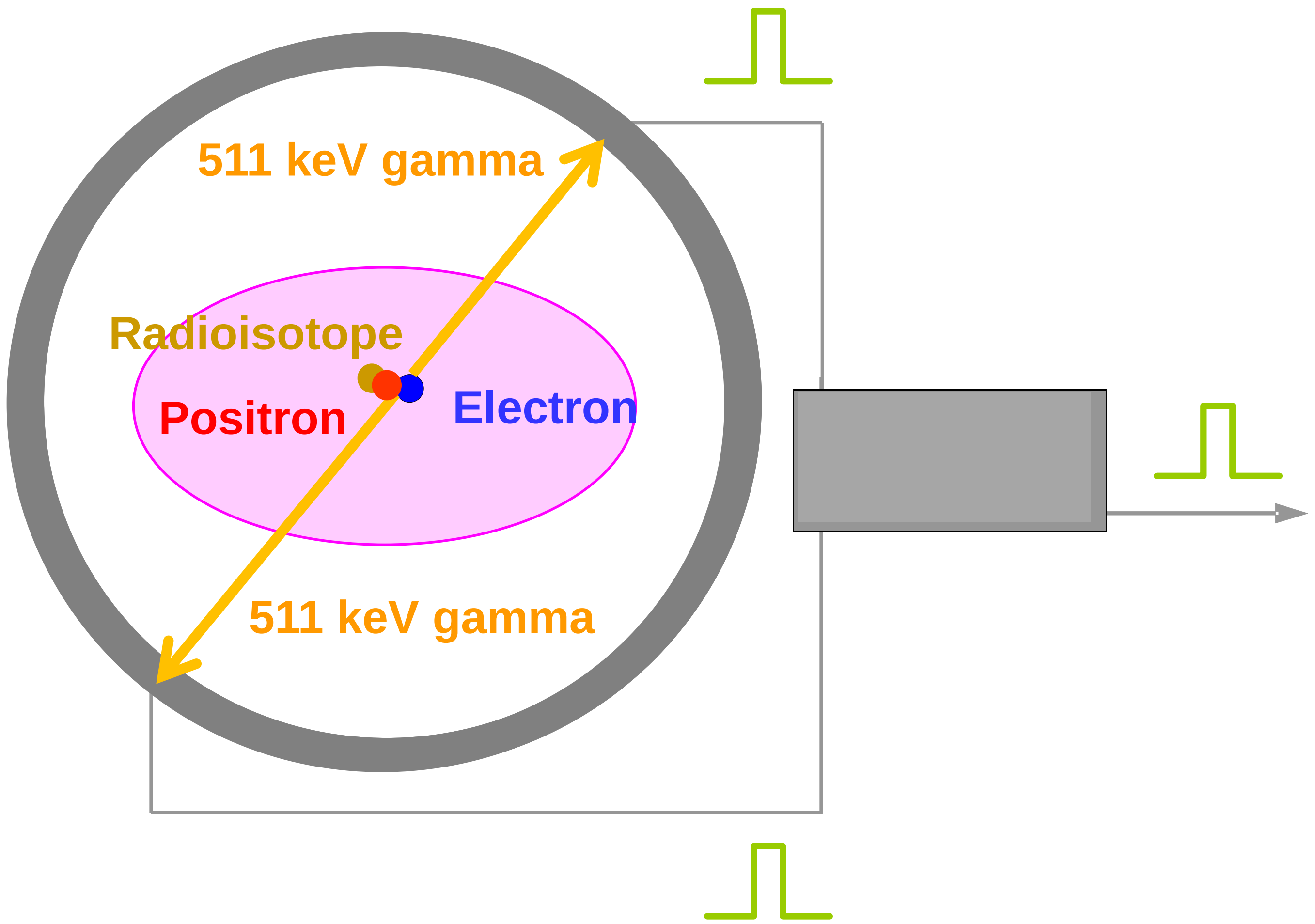


Image gamma rays directly using a gamma camera

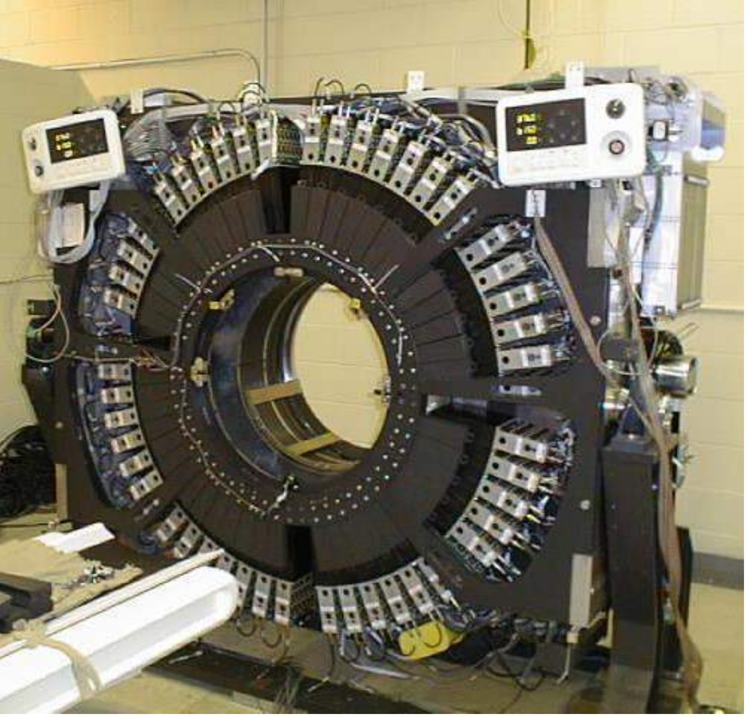
3. TAKE PICTURES

Image positrons indirectly using gamma rays detected by a PET camera

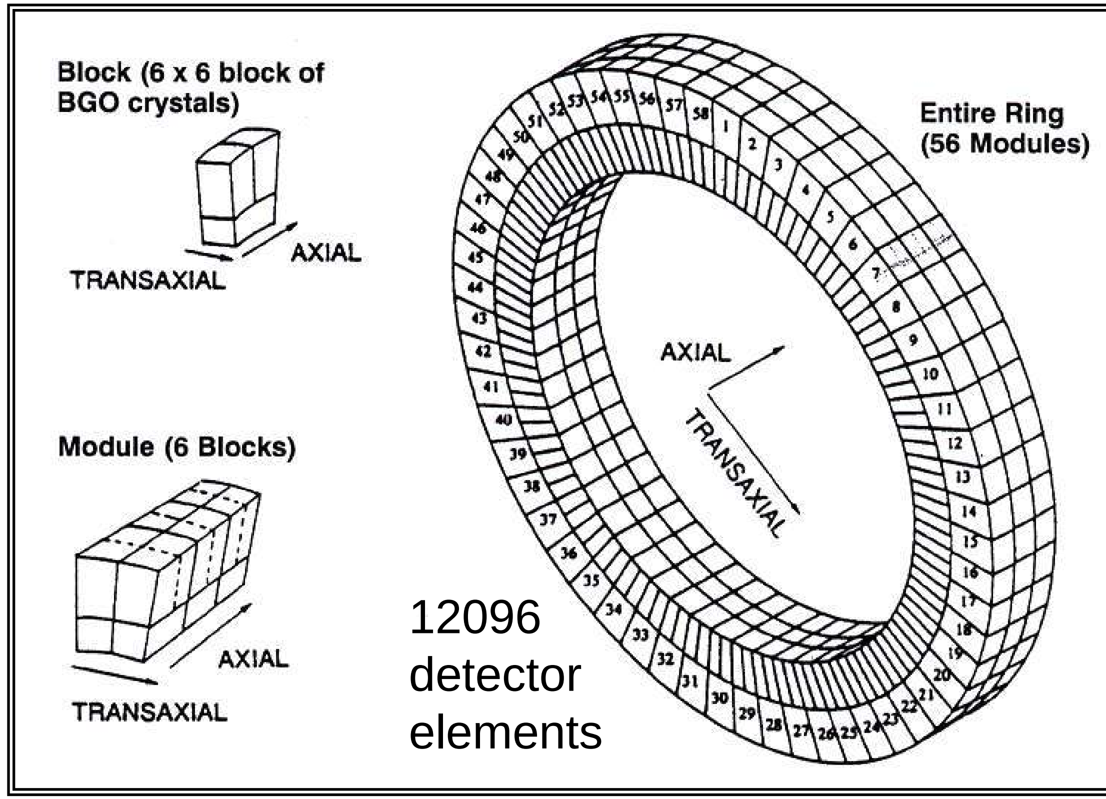
Annihilation and coincidence detection



Full-ring PET detectors



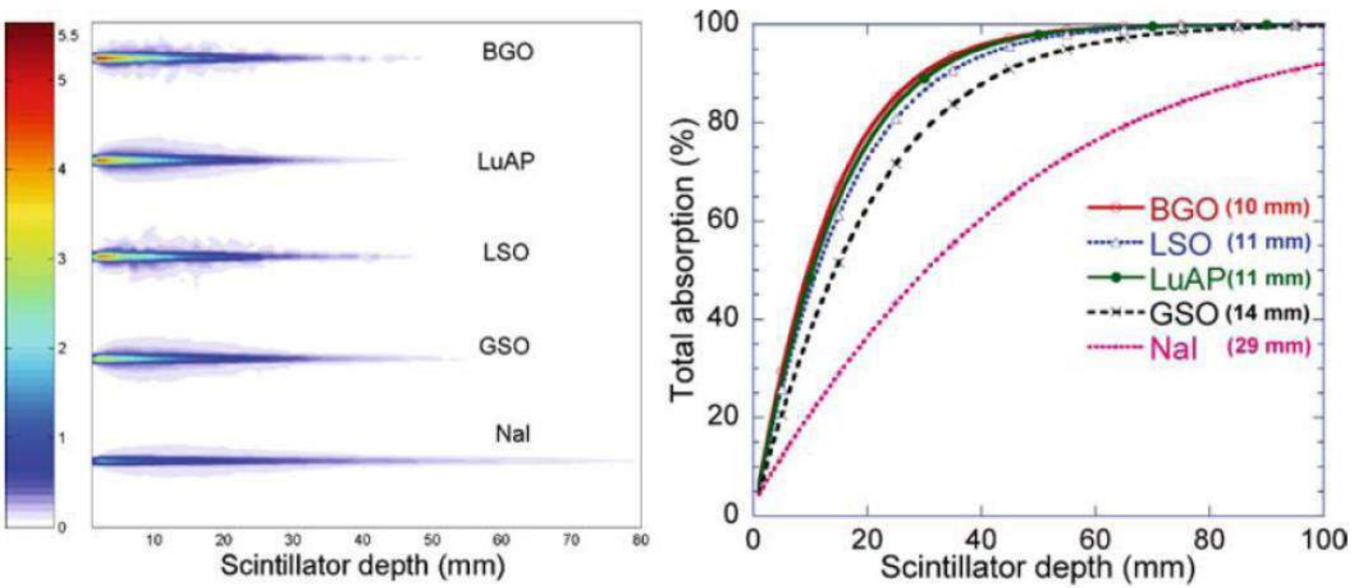
Commercially available in mid-1980s



e.g. GE Advance, installed in Manchester ~2000

Block detector scintillators

Fig. 4. a Monte Carlo calculated histogram distribution of absorbed 511-keV photons in different scintillators as a function of depth for normal photon incidence. The *bar* represents percentage absorbed photons from the total. **b** The cumulative photon absorption probability for 511 keV obtained from the distributions presented in **a**. The value associated with the type of scintillator indicates the depth at which 50% of the incident photons are totally absorbed



Comparison Between Main Physical Properties of PET Scintillation Crystals

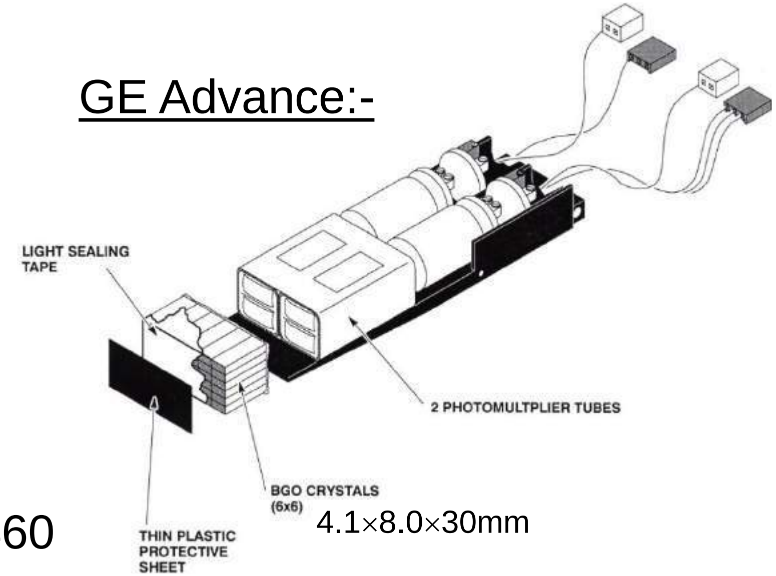
Crystal	Relative light output (%)	Decay time (ns)	Density ($g \cdot cm^{-3}$)	Effective atomic number (Z)	Energy resolution at 511 keV (%)
NaI(Tl)	100	230	3.7	50	8
BGO	15	300	7.1	73	12
LSO	50–80*	40	7.4	65	10
GSO	20–40*	60	6.7	58	9

*Light output depends on cerium concentration and read-out device (PMT or APD).
All crystals emit light with wavelengths ranging from 410 to 480 nm.

Sanchez-Crespo & Larsson 2006, EJNMMI 33:8; Tarantola et al 2003, JNM 44:756

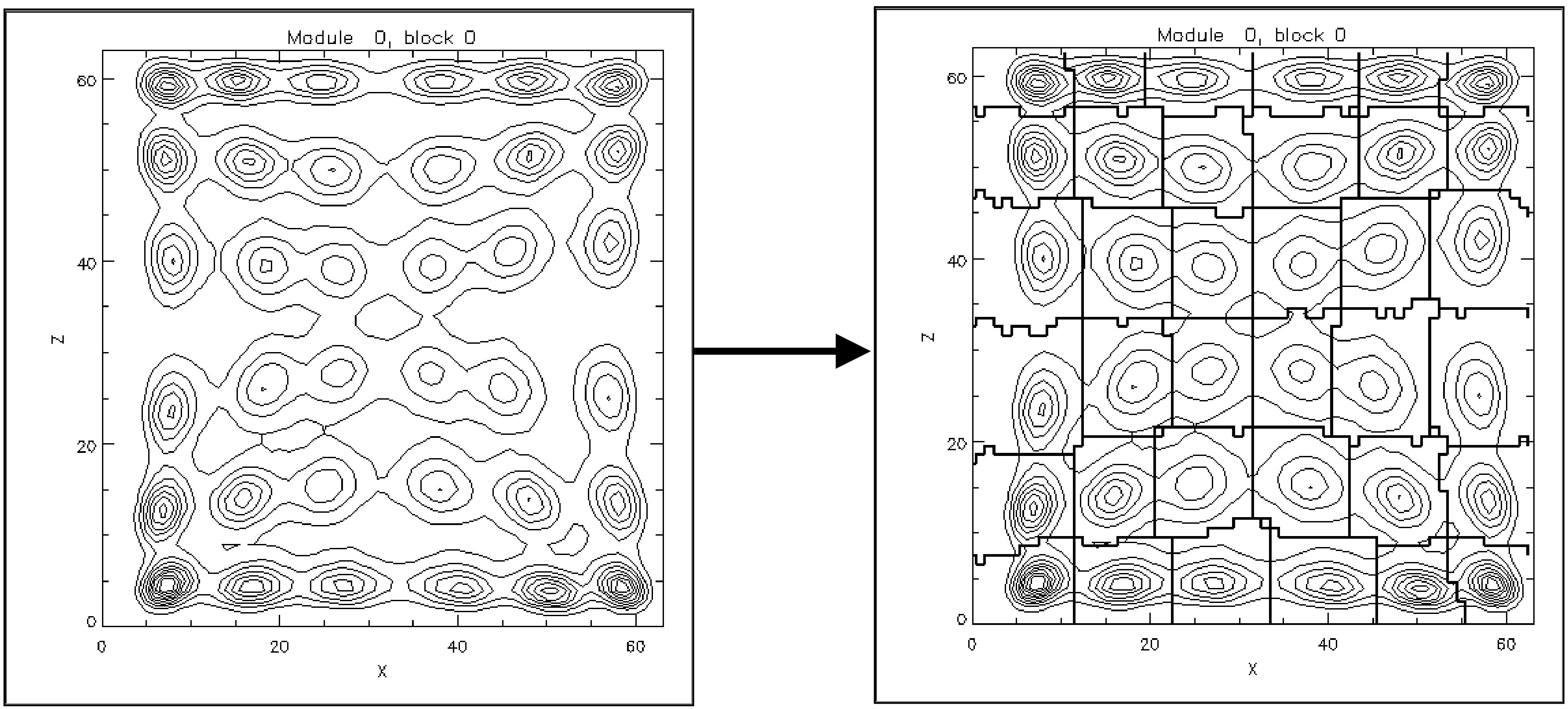
Block Construction

GE Advance:-



4.1×8.0×30mm

from Casey & Nutt. 1986 IEEE-TNS NS-33:460



32448 detector elements

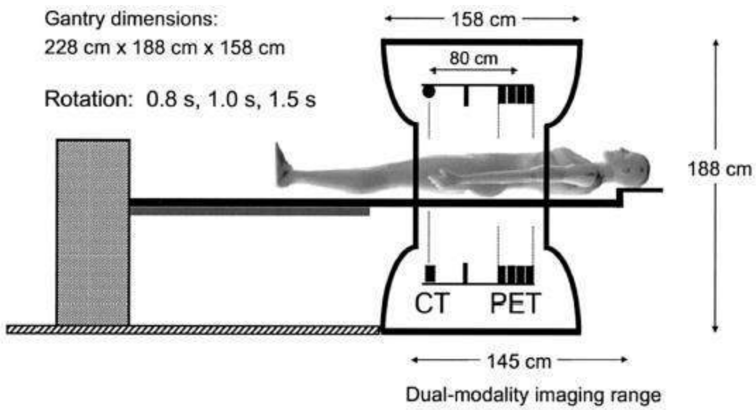
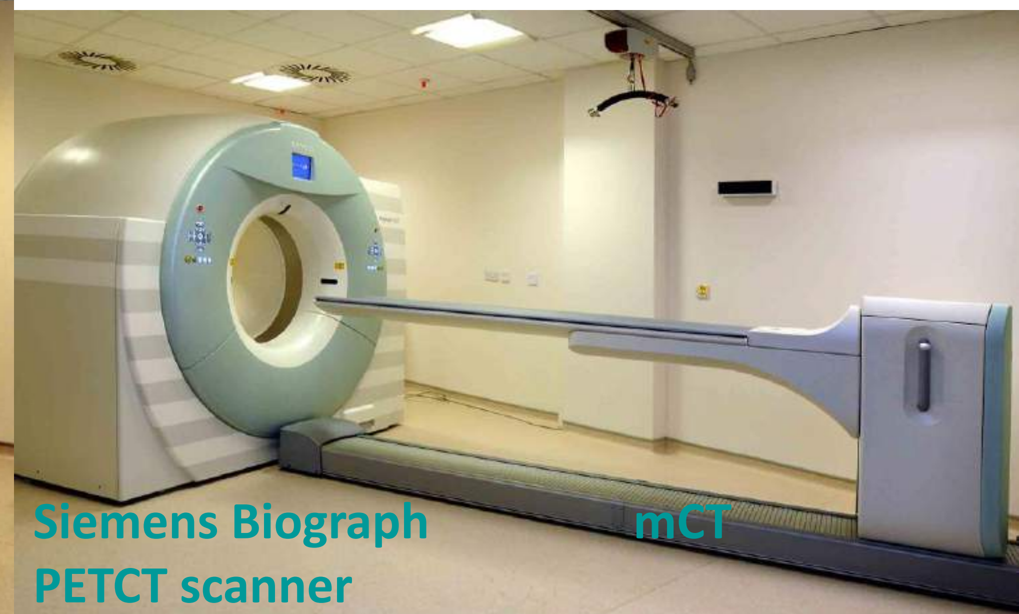


Fig 3. A schematic of the biograph PET/CT scanner. The axial separation of the two imaging fields is 80 cm. The co-scan range for acquiring both PET and CT is 145 cm maximum.

<u>From:</u> Townsend et al. 2003 Sem Nucl Med 33: 193

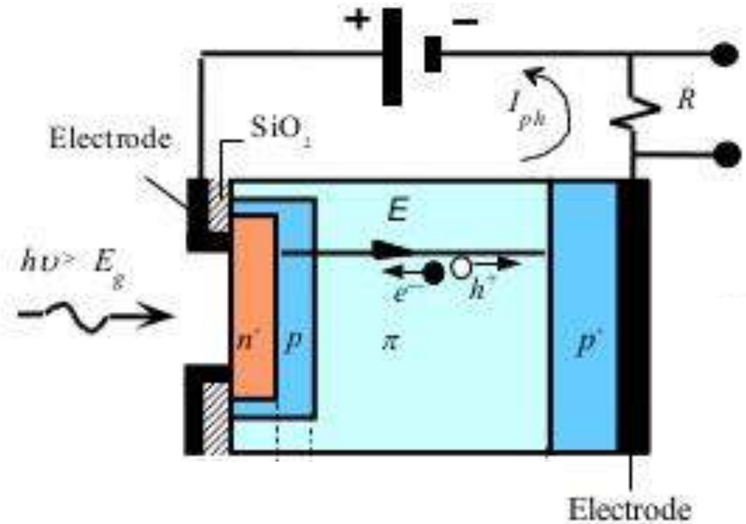


Siemens Biograph mCT PETCT scanner

More recent developments

PETMR

APD vs SiPM

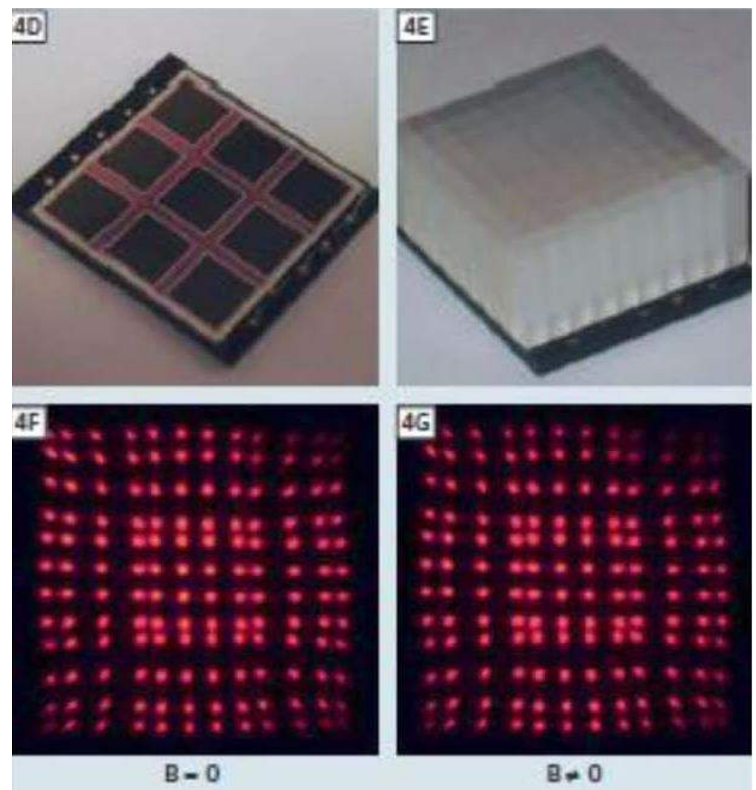


APDs generate signal proportional to energy deposited by photons

SiPMs use arrays of APDs operated in Geiger mode above breakdown voltage

Both resistant to magnetic fields, but need to be operated under carefully-controlled conditions

e.g. scintillator + APDs



Beyer T et al Magnetom FLASH 2010

More recent developments

PETMR

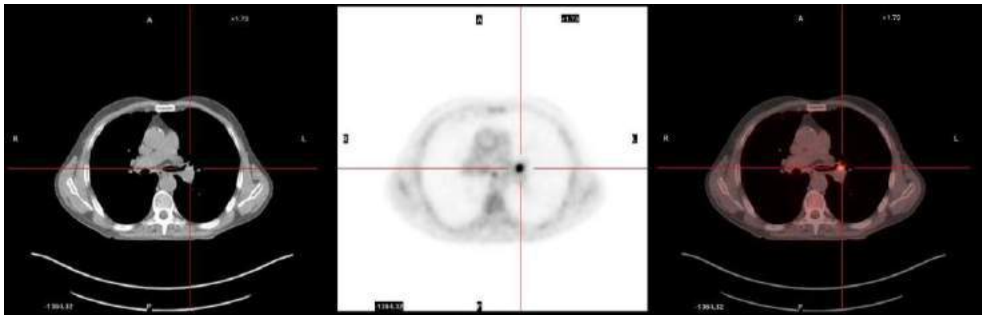
Digital detectors → PETCT

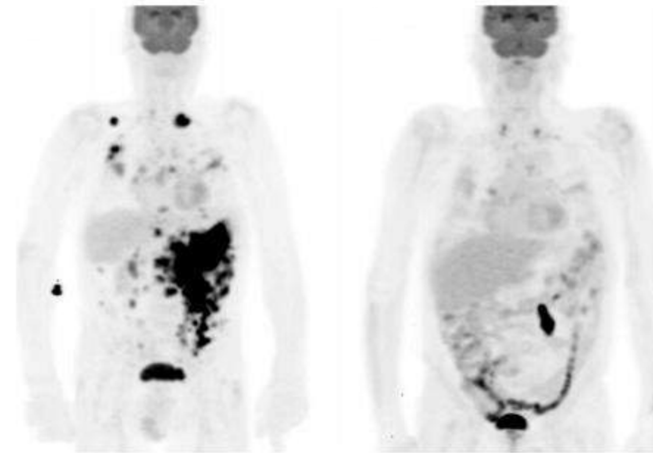
More recent developments

Extended axial field of view scanners

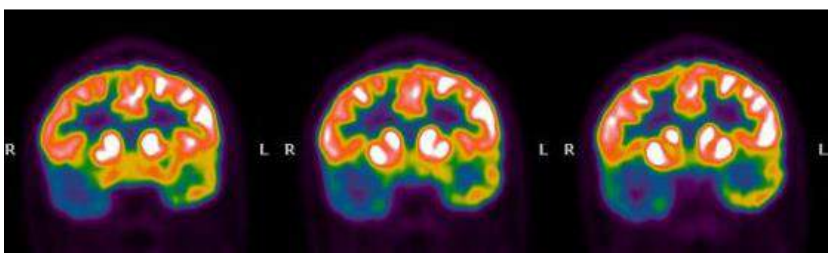
Typical applications

Oncology and Infection

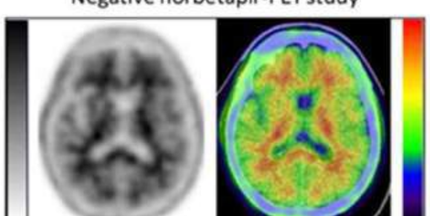




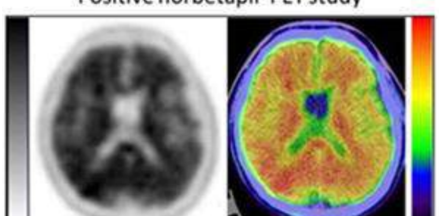
Neurology

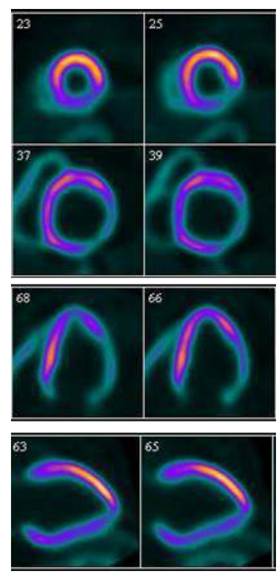


Negative florbetapir-PET study

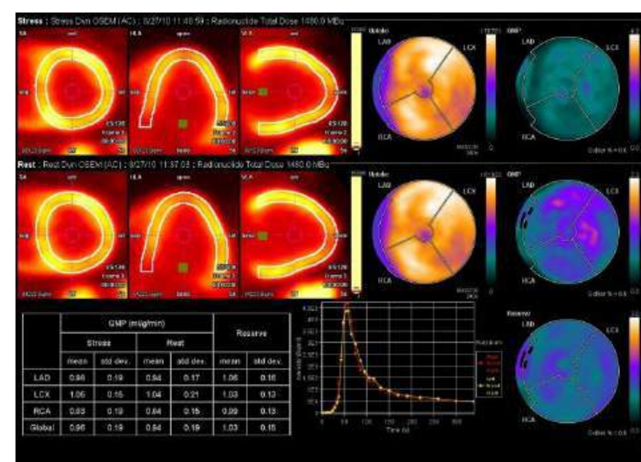


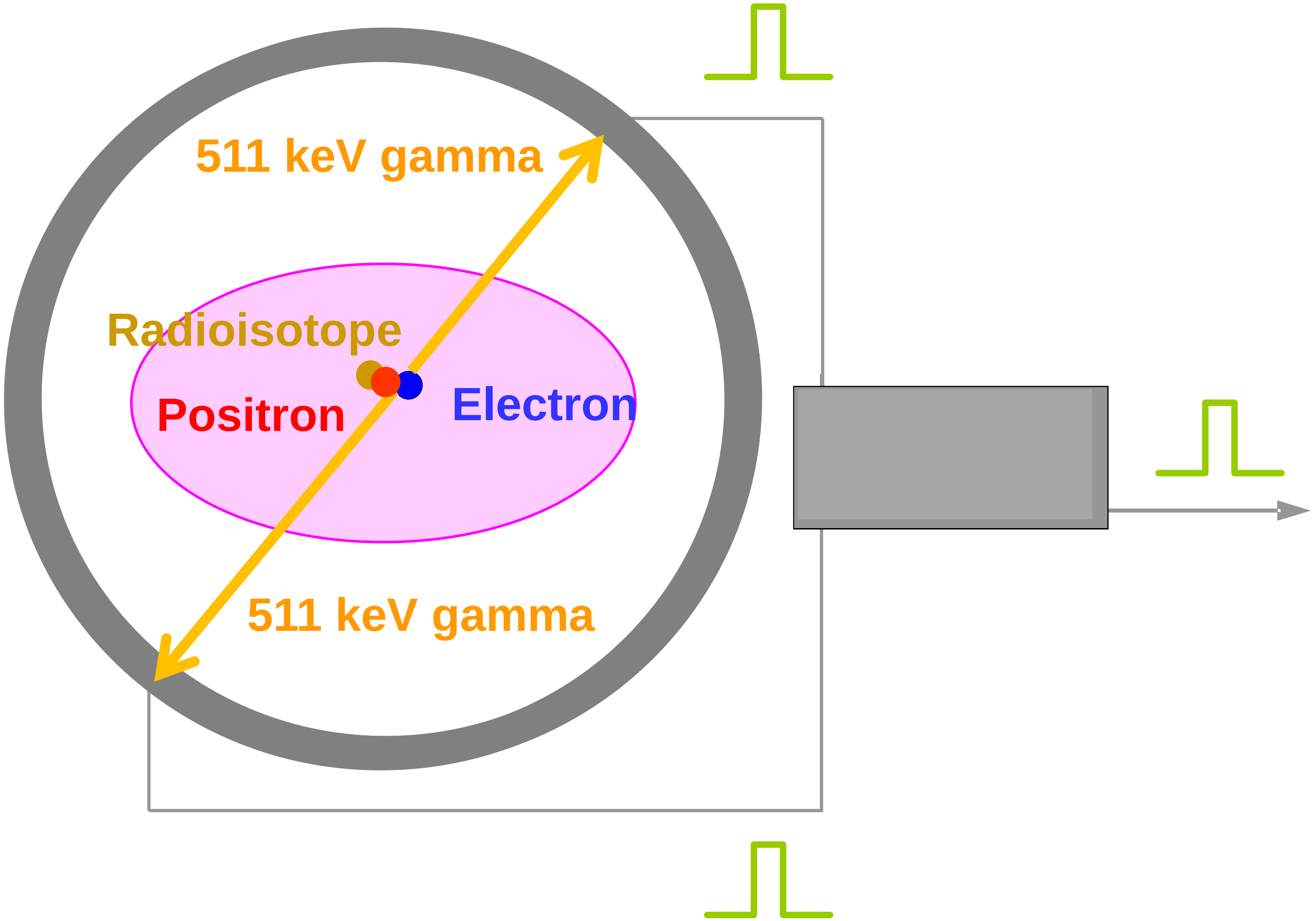
Positive florbetapir-PET study





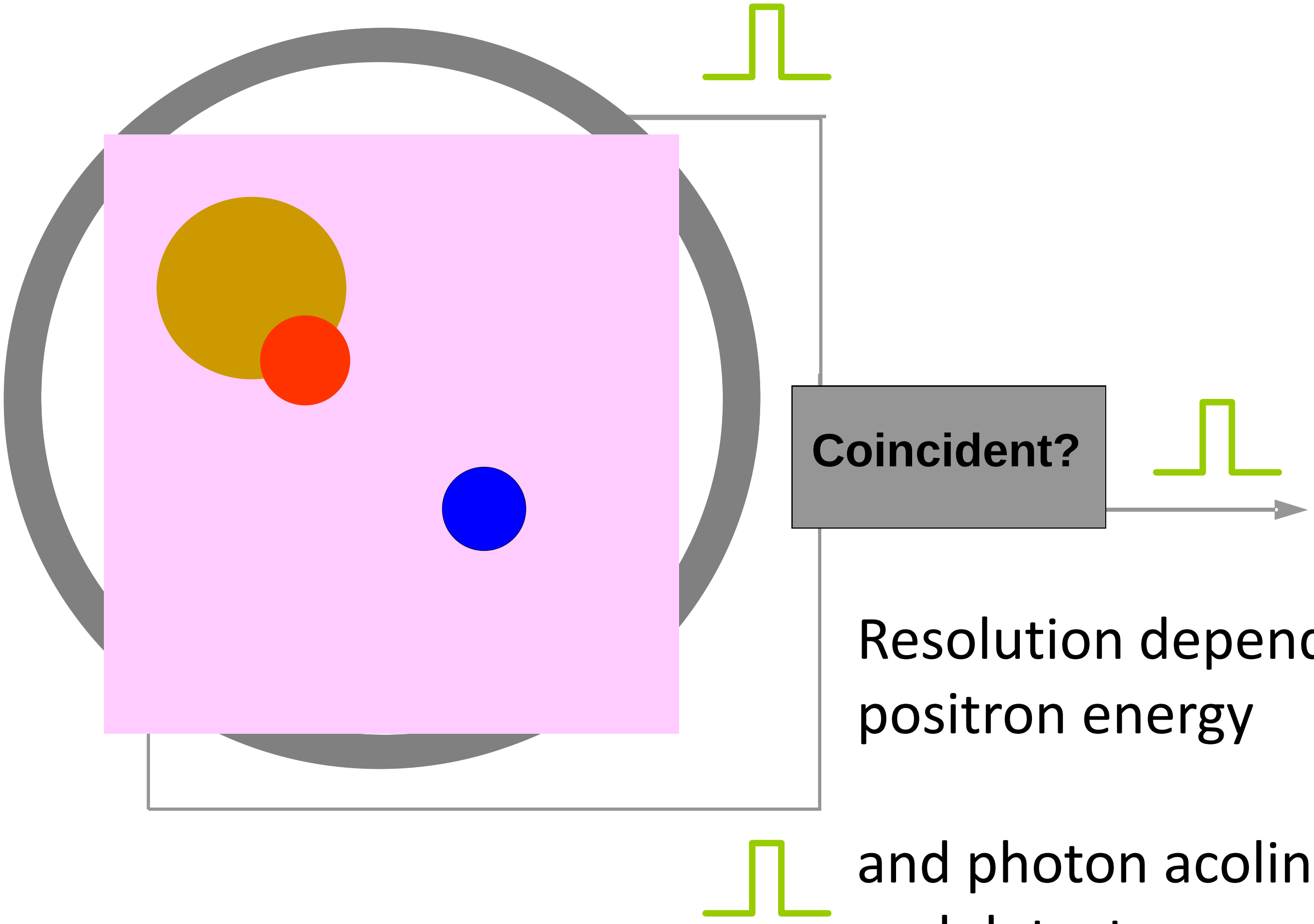
Cardiology





"I think you'll find it's a bit more complicated than that"

Annihilation and coincidence detection

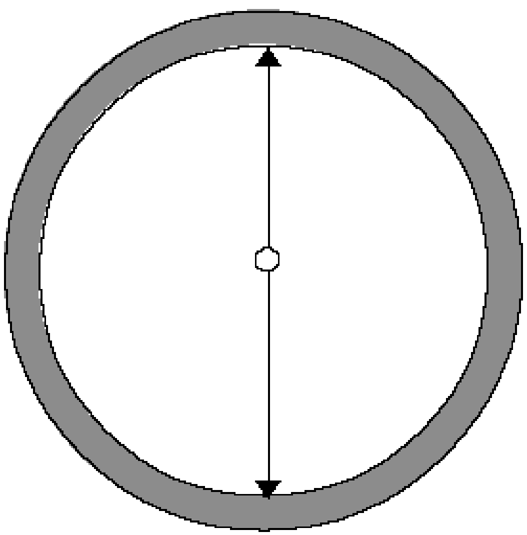


Resolution depends on positron energy

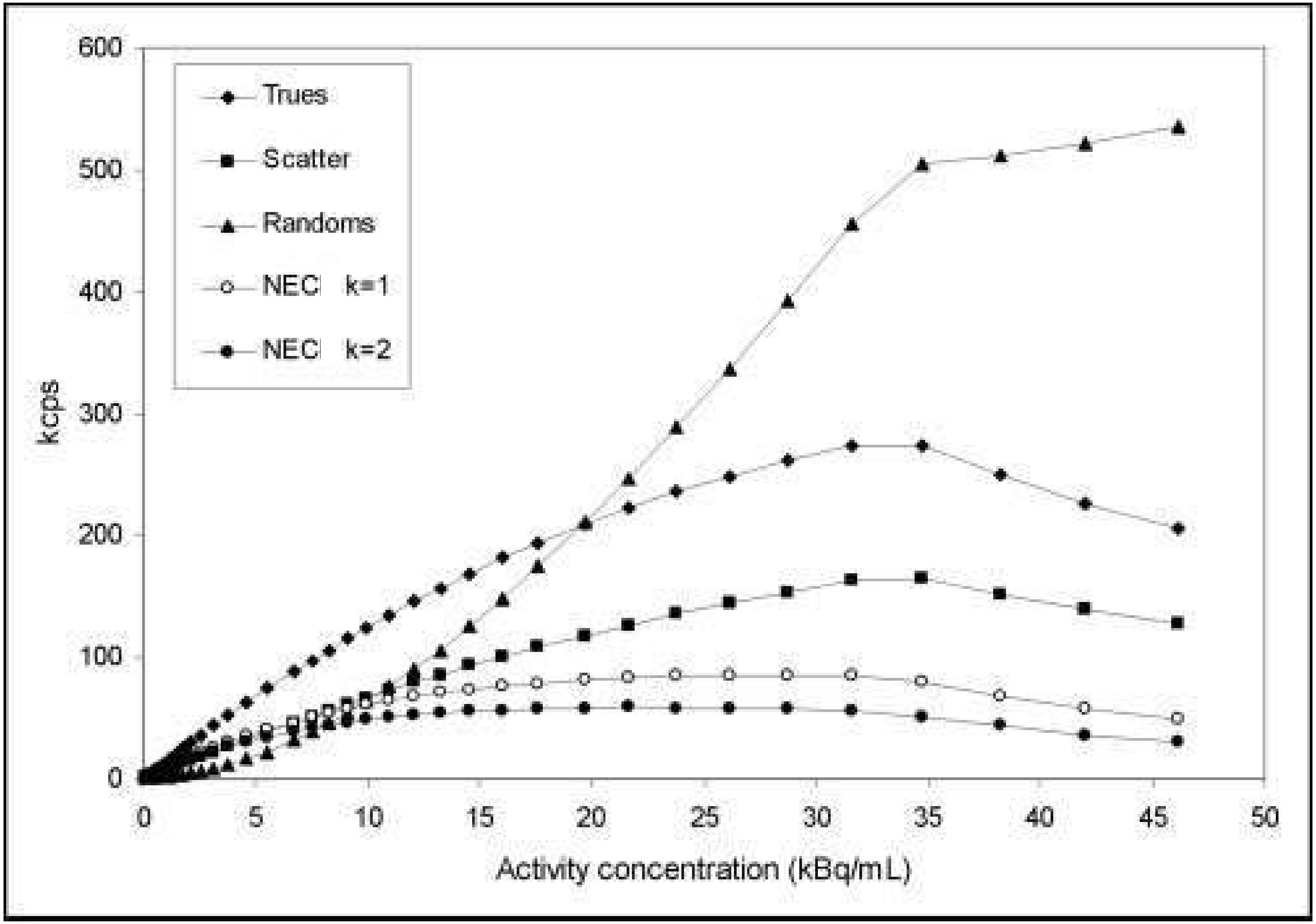
and photon acolinearity
and detector geometry
and image reconstruction

Types of coincidence events in PET

(a) Trues

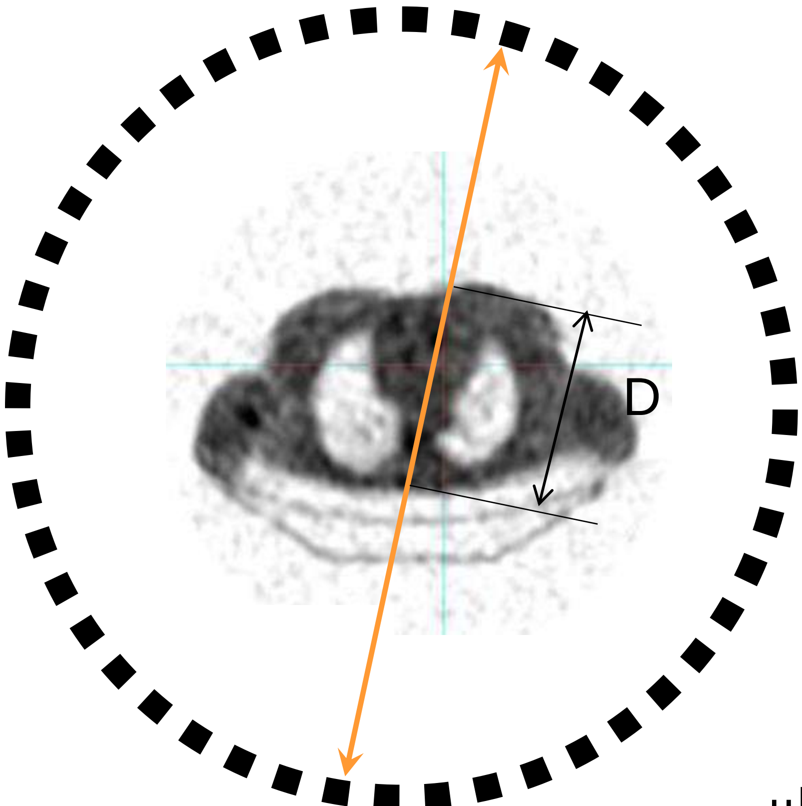


Variation of count rates: example



For PET component of Siemens Biograph PETCT system

from Brambilla et al JNM 2005; 46:2083–2091



$A=A_0e^{-\mu D}$

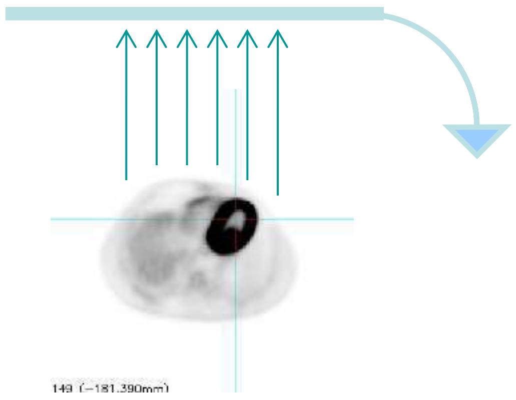
Correct PET data for

- Random coincidences
- Detector deadtime
- Variations in detector sensitivity (normalisation)
- Scattered coincidences
- Attenuation
- Variations in resolution?

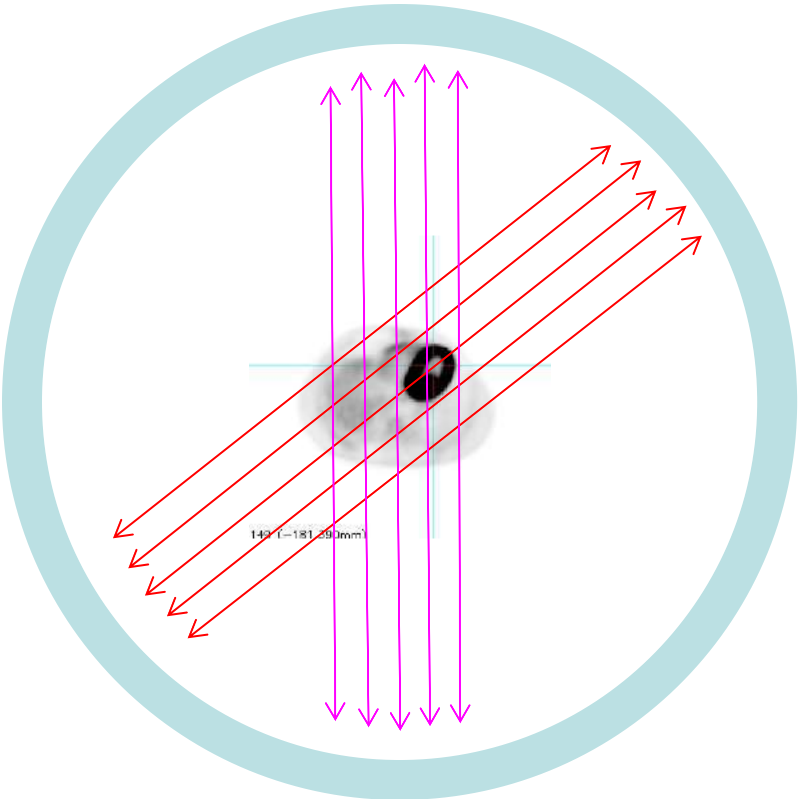
All built into image reconstruction process – varies between algorithms and manufacturers' implementation of those algorithms

How the data is stored

- SPECT
  - Rotating gamma camera head(s)

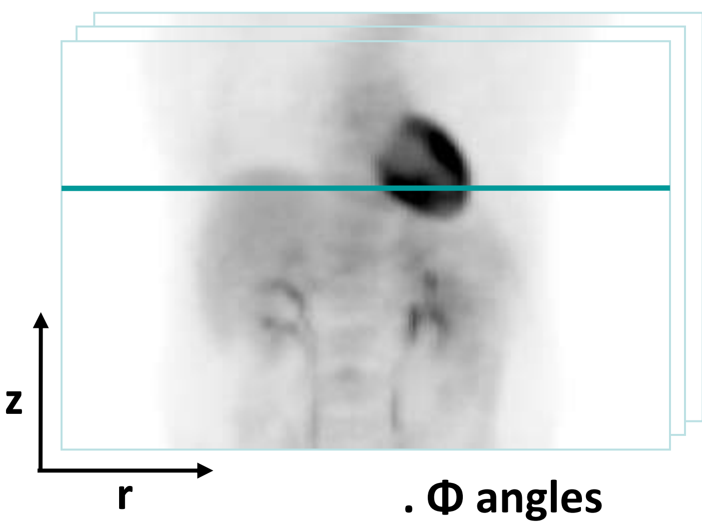


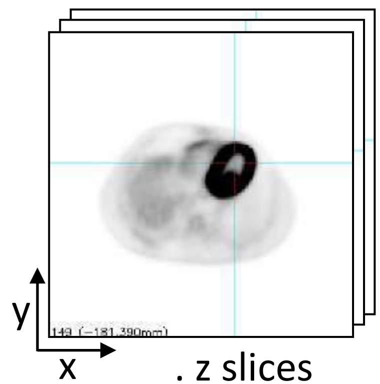
- PET
  - Static ring(s)

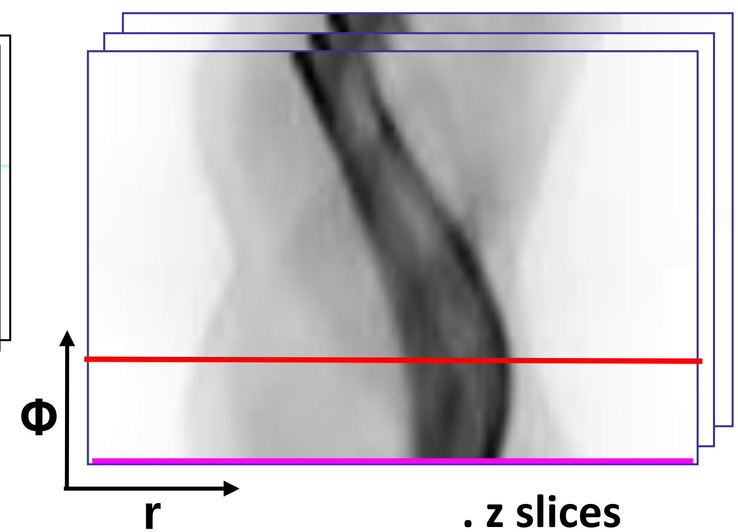


How the data is stored

- SPECT → Projections
  - As these are what we acquire with the detector in any one position.
- PET → Sinograms
  - As PET scanners have rings which naturally lead to these.





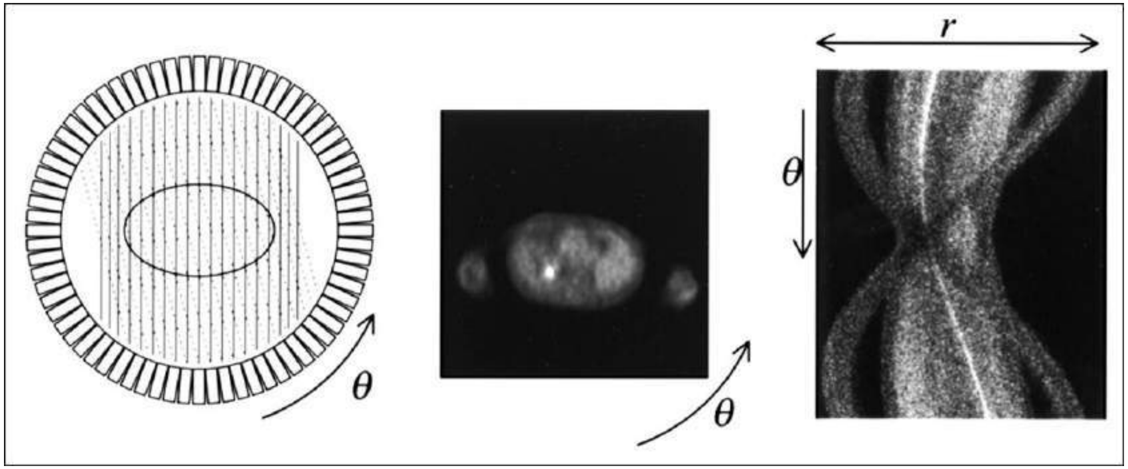


These are exactly the **same data**, just stored slightly differently.

Mathematically it's more natural to reconstruct from sinograms.

How the data is stored

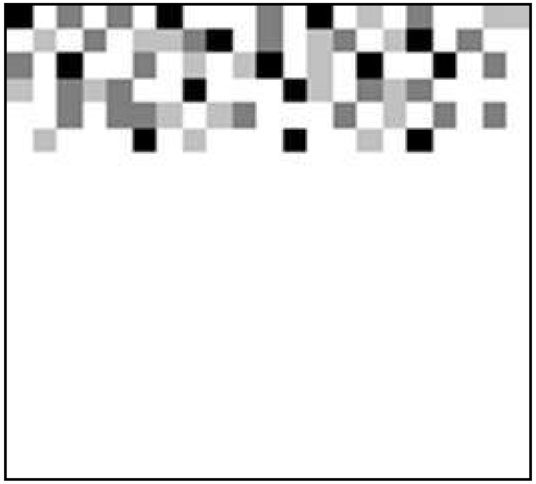
Sinograms



from Turkington

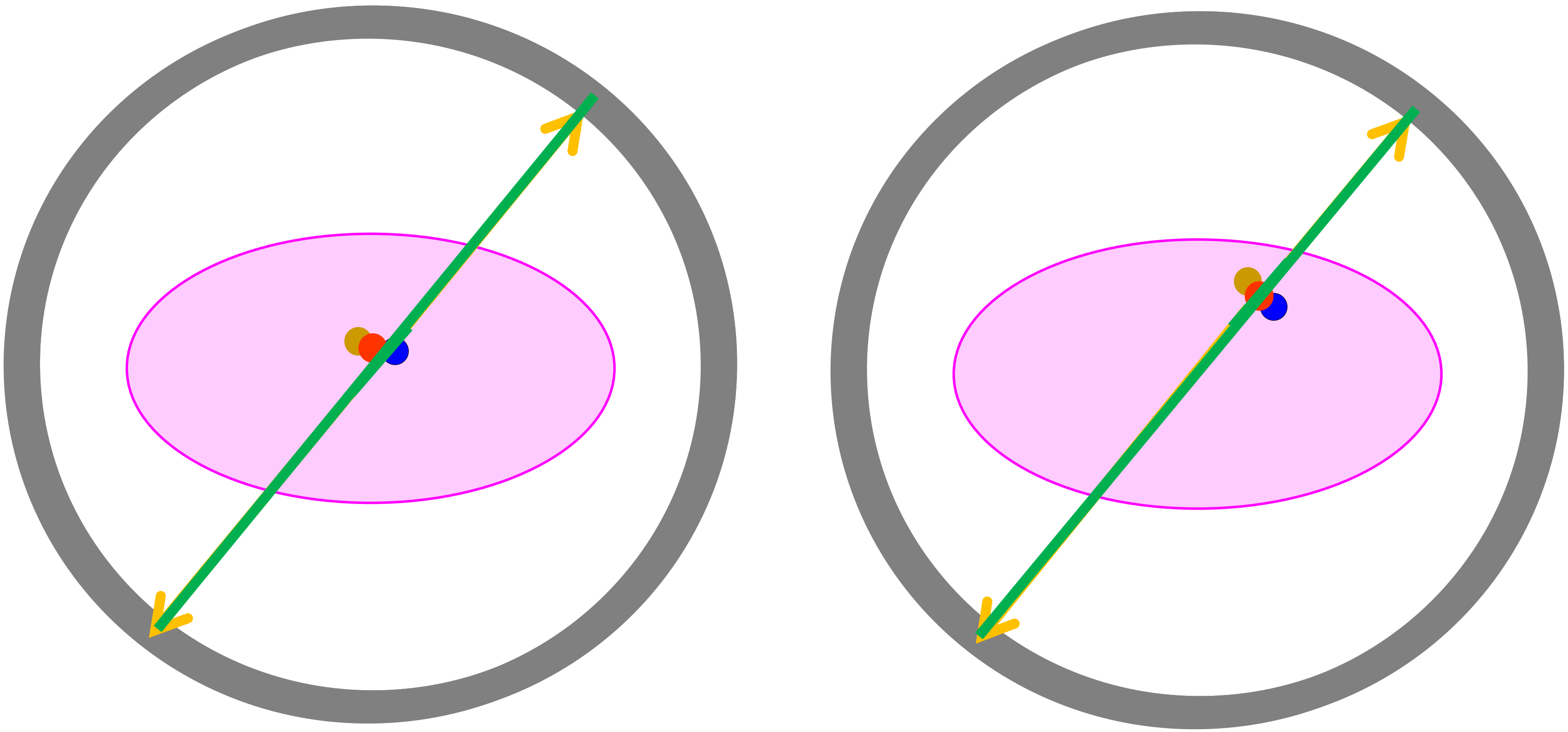
JNMT 2001 29:1–8

List Mode



Record data in simple list –
no real-time image
Include regular time markers and physiological markers (e.g. R wave)
Afterwards replay list to reformat

Annihilation and coincidence detection – improvements with Time of Flight



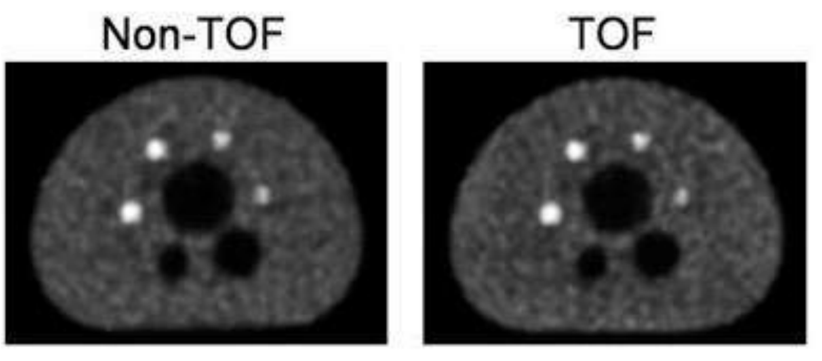
'Standard' PET : positron could have met electron anywhere along the line of response

Time of flight PET : time difference between detecting gamma rays locates positron-meets-electron more accurately

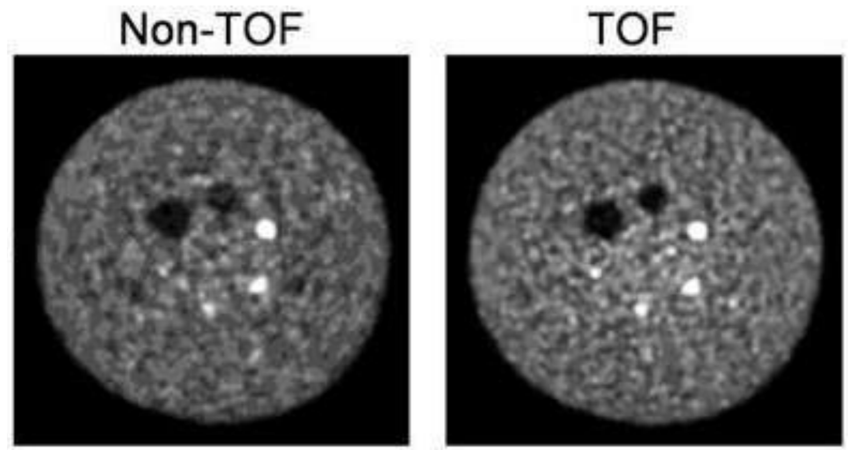
First "Time-of-Flight" capable ring systems

GEMINI TF (timing resolution 0.7ns)

LIGHT

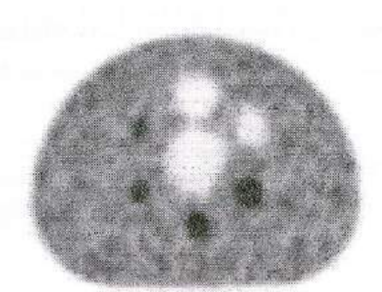


HEAVY

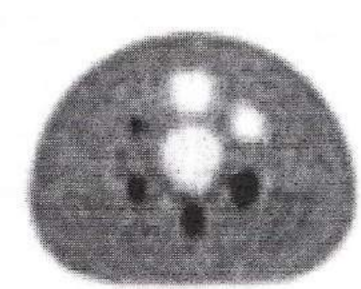


DISCOVERY ST

LIGHT (2D)



LIGHT (3D)



ToF gives better signal to noise and hence better image quality, particularly in large patients

Can be used to reduce patient dose and/or scanning time

Pixel values in PET images

$\propto$

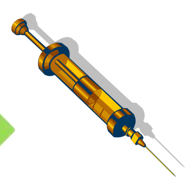
radioactivity concentration (kBq/ml)

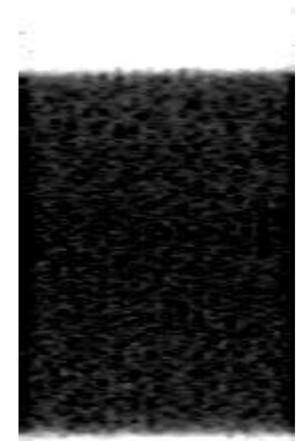
Calibration

ml

kBq/ml

SCAN



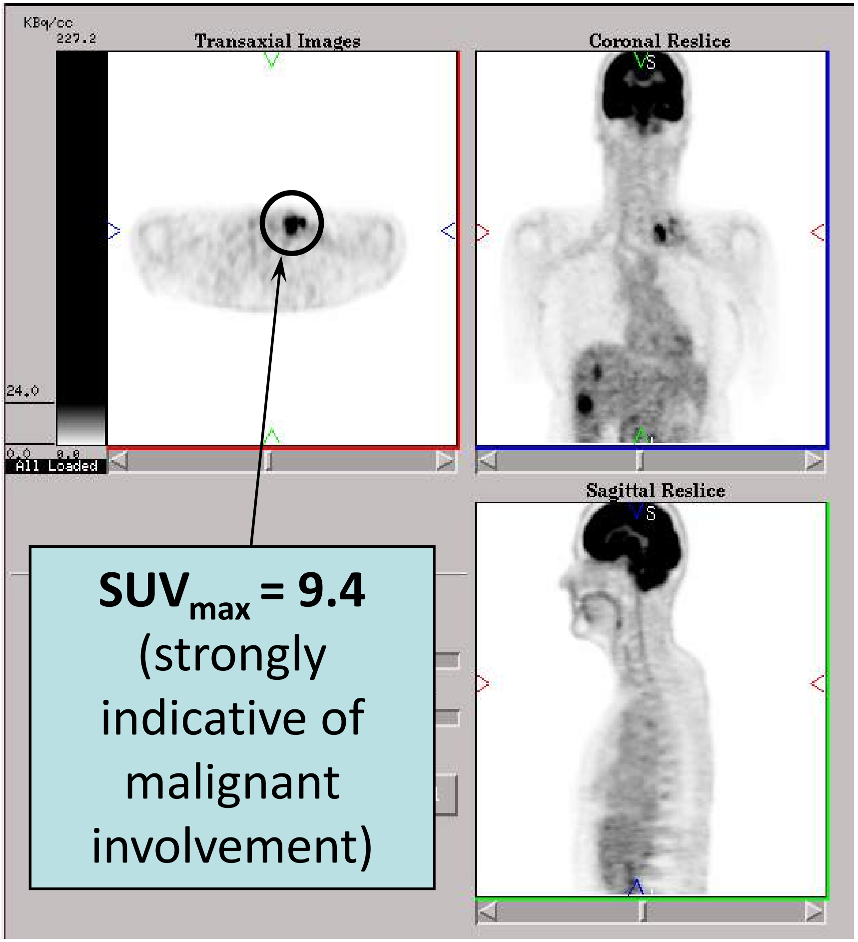


kBq

Average pixel value represents known kBq/ml

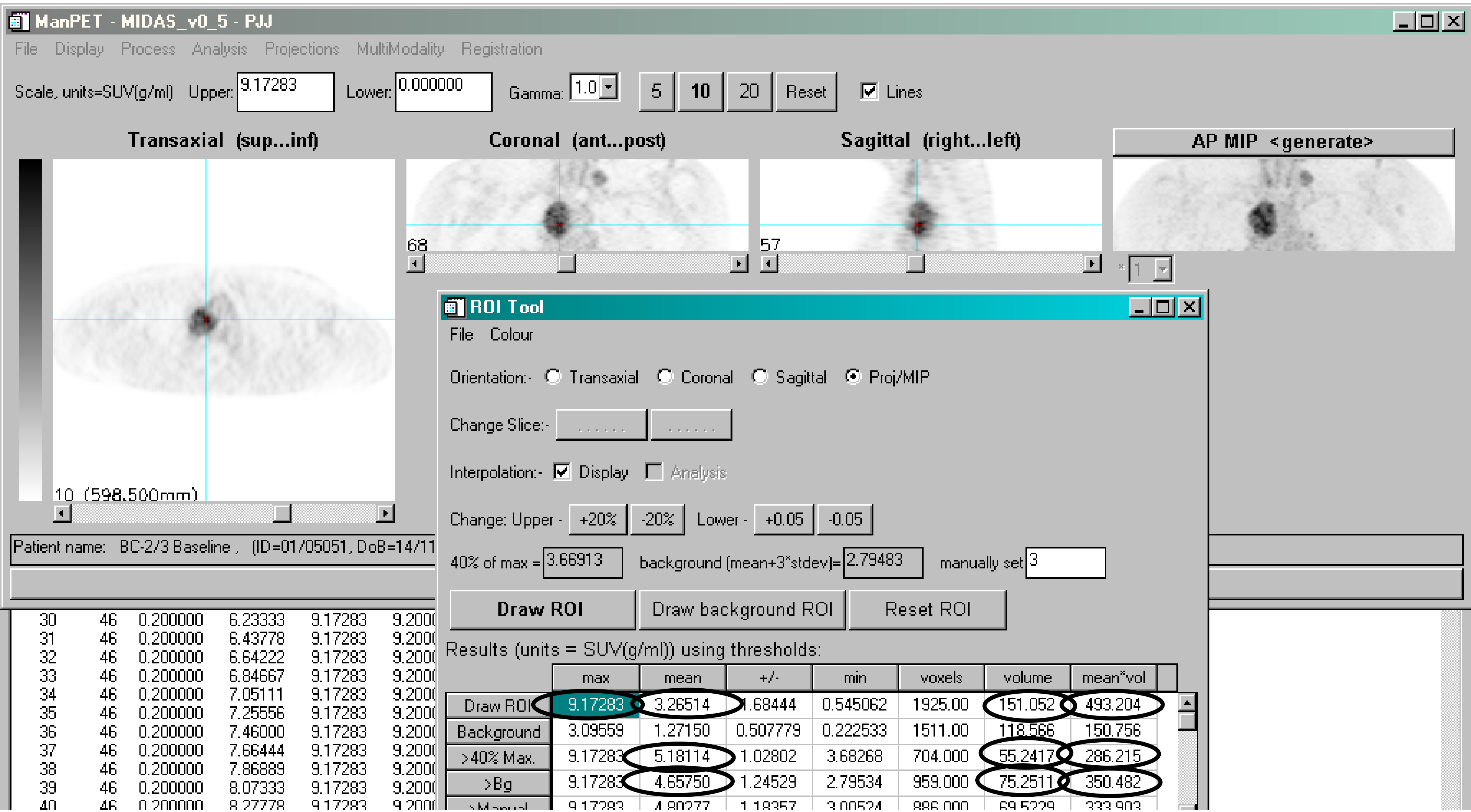
Standardised uptake value (SUV)

With all appropriate corrections and calibrations the uptake may be expressed in absolute terms using SUV, which accounts for variations in injected activity and patient weight

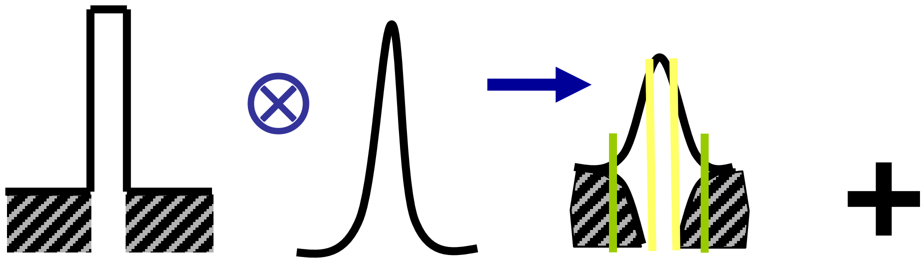


$$SUV(g/ml) = \frac{\text{radiotracer conc.(kBq/ml)}}{\text{admin.activity(MBq)/patient weight(kg)}}$$

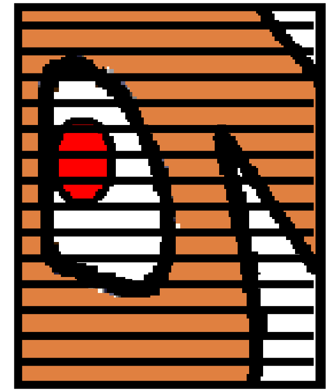
SUV – so, how many numbers would you like?



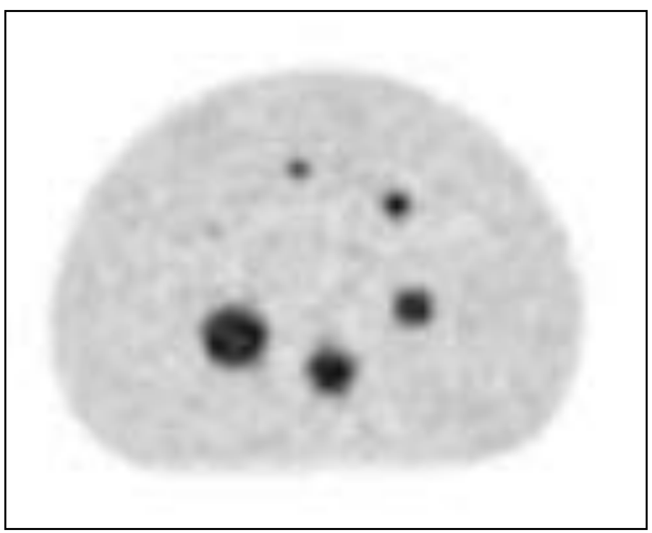
Measured concentration depends on VOI analysis…



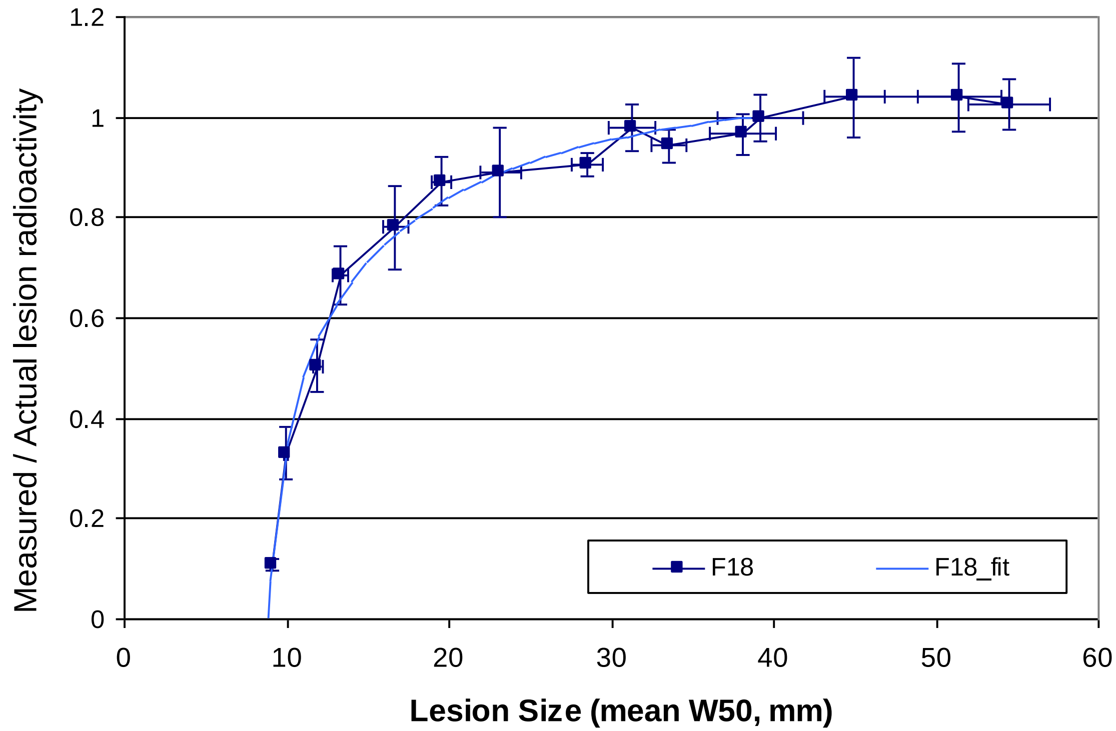
Recovery loss and spillover



Partial volume effect



…and lesion size



Quantitative PET

Need to standardise :

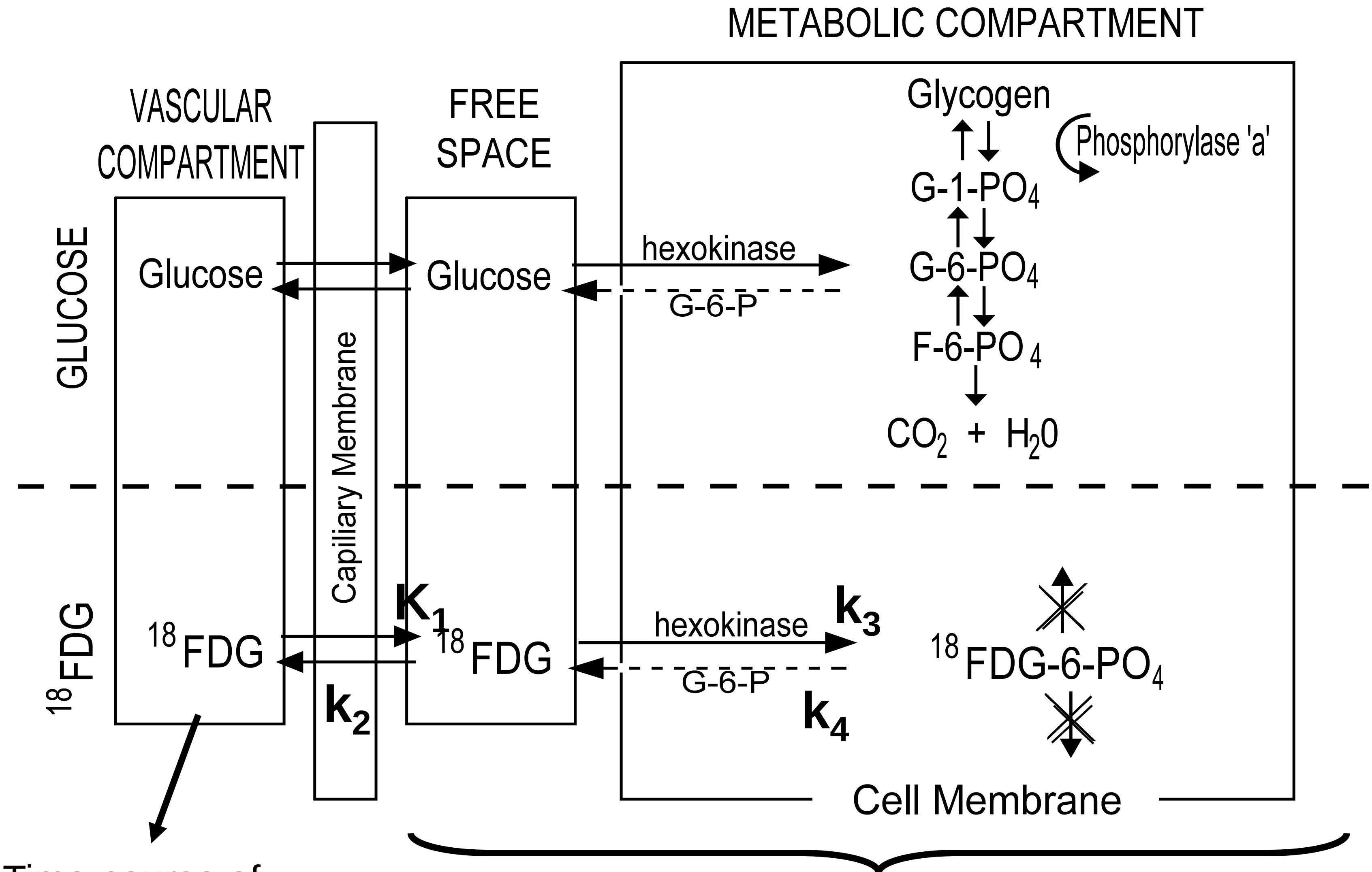
- Patient preparation
- Image acquisition
- Image reconstruction
- ROI and VOI analysis

Lesion size will vary – how account for when reporting?

Quantitative PET - kinetic analysis

- Generates biochemical rate constants for processes in uptake mechanism
- Results are potentially more indicative of tissue behaviour than simple uptake measures at fixed time after injection (such as SUV)
- Requires time-course of radioactivity concentration in blood and tissue, and compartmental model

Kinetic analysis – e.g. FDG



Time-course of 18FDG in blood

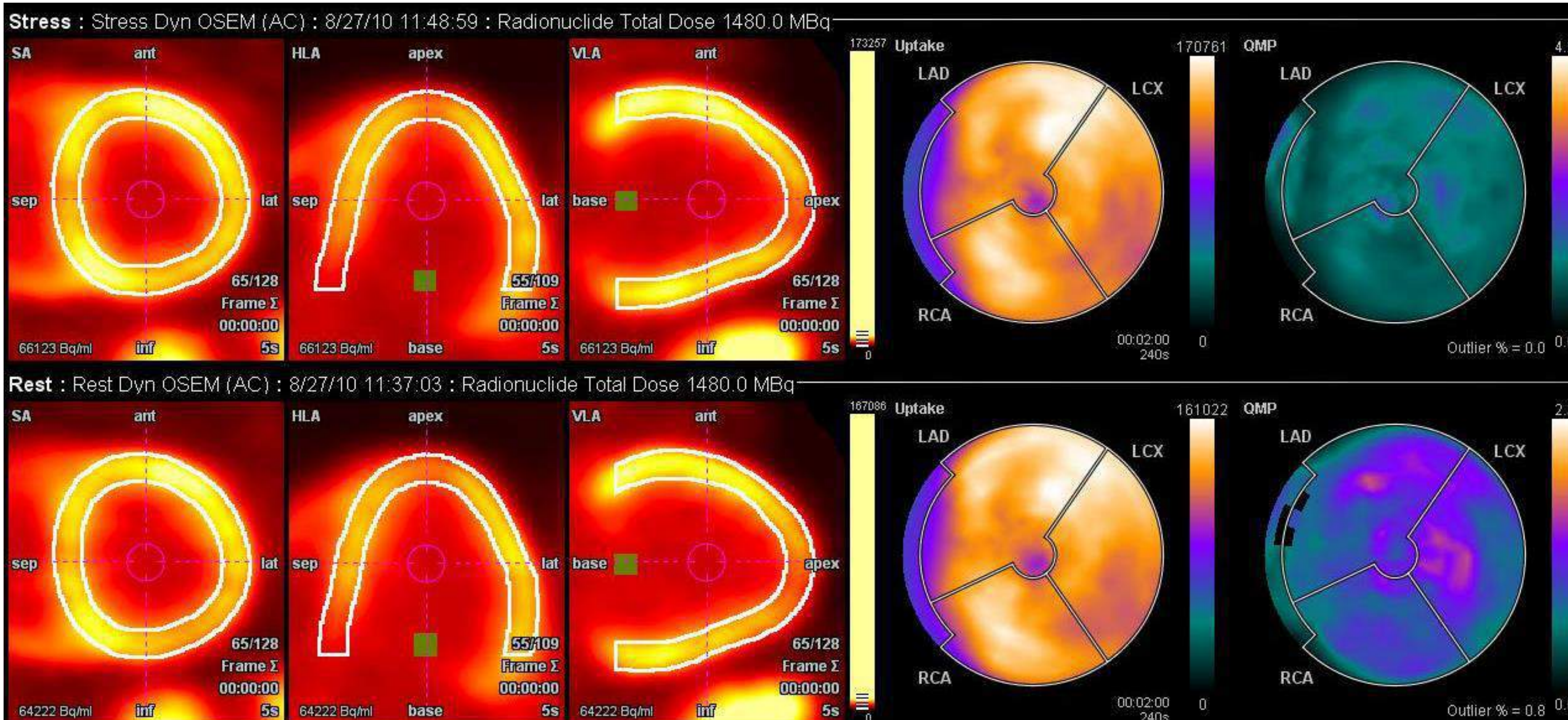
Time-course of 18F activity in tissue

Kinetic analysis with FDG – in practice

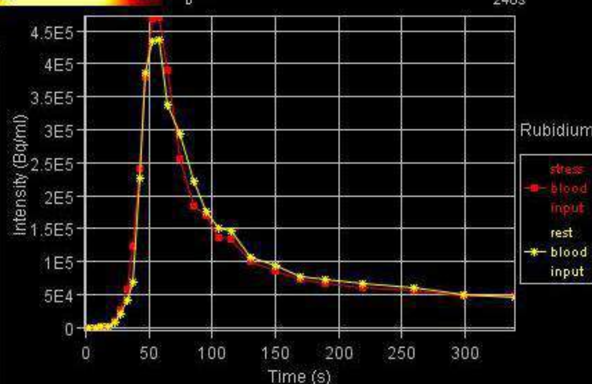
- Quantitative dynamic imaging
- Blood sampling
  - Traditionally arterial
  - Can use venous with heated hand, population reference or image-derived (± normalisation to concentration in venous samples)
- Analysis
  - Non-linear fitting to model
  - Simplified approaches, eg. Patlak graphical analysis (assumes k_4 negligible)

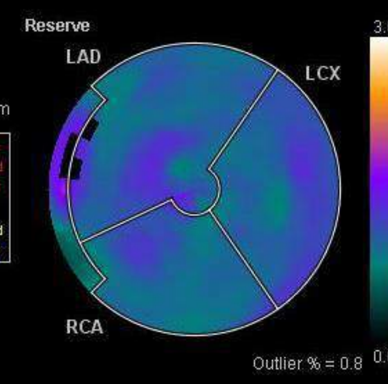
Examples of PET kinetic analysis in clinical practice

Non-linear fit to model – rMBF using ^{82}Rb

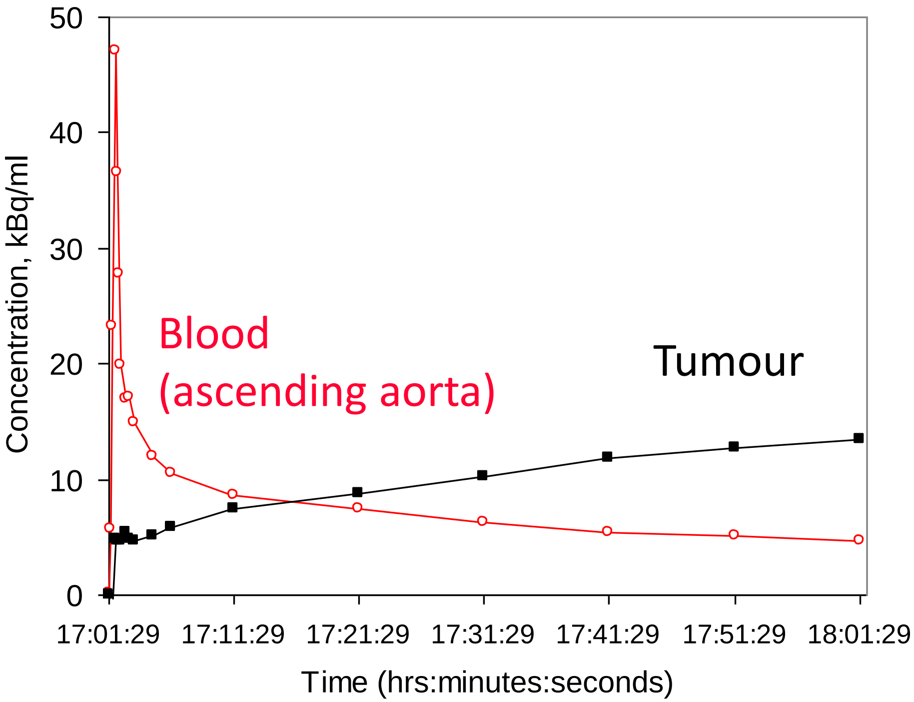


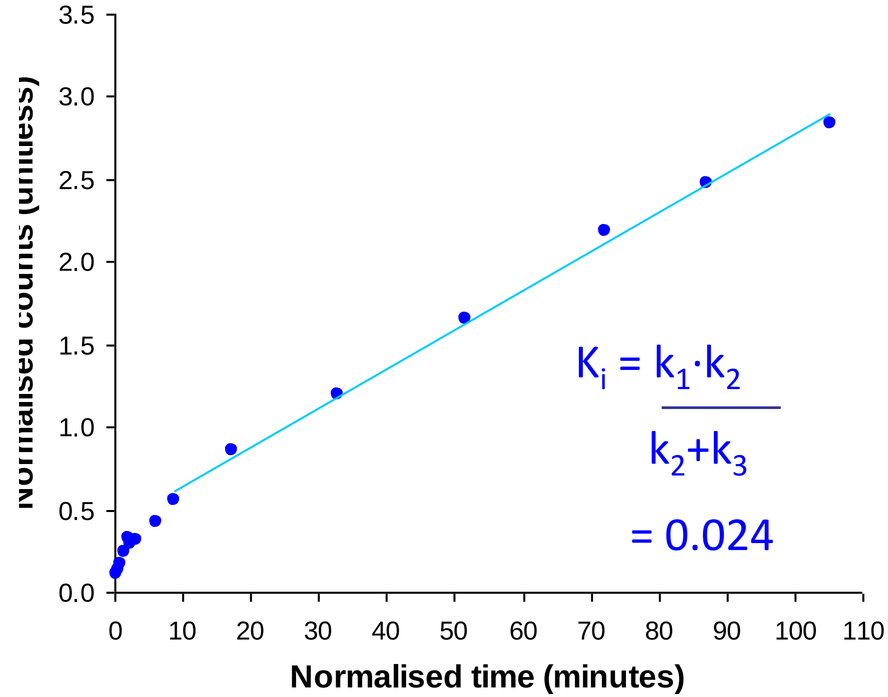
	QMP (ml/g/min)				Reserve	
	Stress		Rest			
	mean	std dev.	mean	std dev.	mean	std dev.
LAD	0.98	0.19	0.94	0.17	1.06	0.16
LCX	1.05	0.15	1.04	0.21	1.03	0.13
RCA	0.83	0.19	0.84	0.15	0.99	0.13
Global	0.96	0.19	0.94	0.19	1.03	0.15





Patlak Analysis – FDG in lung tumour





Refs: Patlak et al 1983 J Cereb Blood Flow Metab 3:1
or Peters 1994 Nucl Med Comm 15:669 (recommended!)

Manufacturers are now developing Patlak-based approaches for parametric imaging

Thanks for listening!
Any questions?

@alrightPET