

# Physical performance of the first total-body EXPLORER PET scanner and preclinical applications with mini-EXPLORER systems

+ first human images!

Eric Berg, Weiping Liu, Yong Zhao, Yun Dong, Yang Lv, Xinyu Lv, Tianyi Xu, Zilin Deng, Yu Ding, Xuezhu Zhang, Martin S. Judenhofer, Jinyi Qi, Terry Jones, Jun Bao, Hongdi Li, Ramsey D. Badawi, Simon R. Cherry

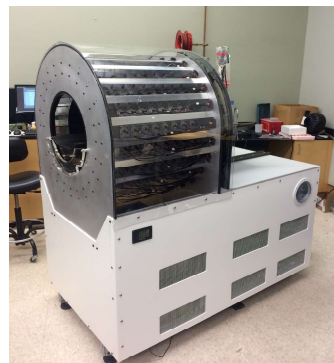


[explorer.ucdavis.edu](http://explorer.ucdavis.edu)

# Disclosures

- UC Davis has a sales-based gift agreement with United Imaging Healthcare.
- *uEXPLORER* total-body PET scanner is not FDA approved.

# The EXPLORER Project



## MiniEXPLORER-I

- Applications prototype
- Nonhuman primate imager
- Siemens technology platform



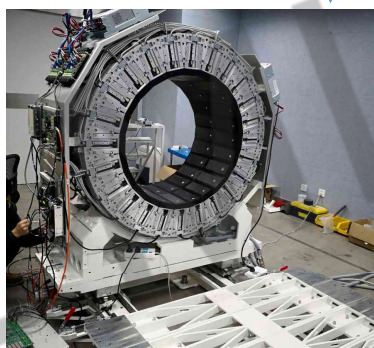
## MiniEXPLORER-II

- Technology prototype for *uEXPLORER*
- Companion animal/human brain imager
- UIH technology platform



## PennPET EXPLORER

- High TOF resolution
- Torso imager
- Philips technology platform



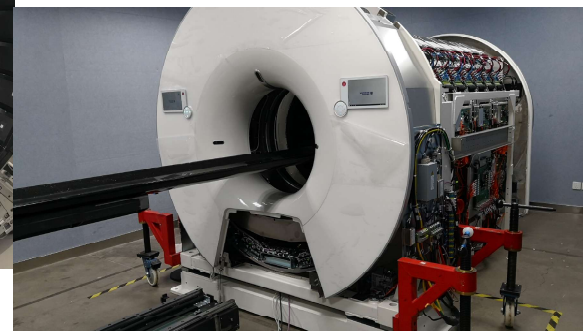
## *uEXPLORER*

- High spatial resolution
- Total-body imager
- UIH technology platform

Jan 2018

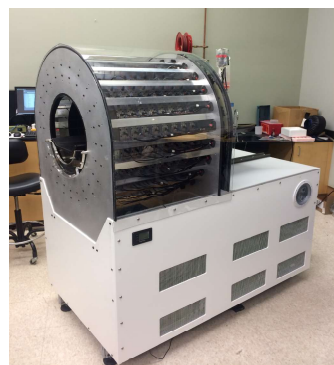


March 2018



April 2018

# The EXPLORER Project



## MiniEXPLORER-I

- Applications prototype
- Nonhuman primate imager
- Siemens technology platform



## MiniEXPLORER-II

- Technology prototype for uEXPLORER
- Companion animal/human brain imager
- UIH technology platform



## PennPET EXPLORER

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## uEXPLORER

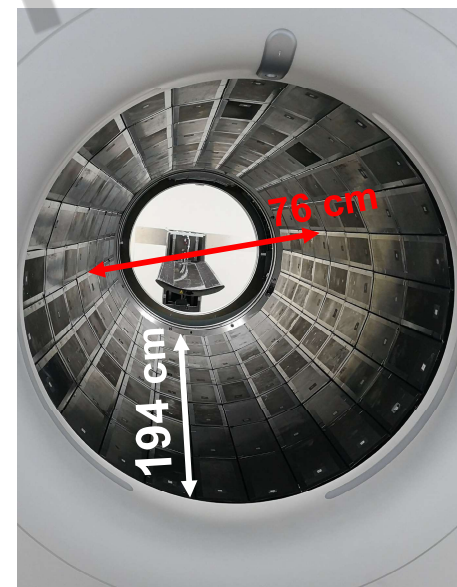
- High spatial resolution
- Total-body imager
- UIH technology platform

**uEXPLORER  
construction  
completed!**



# uEXPLORER: overview

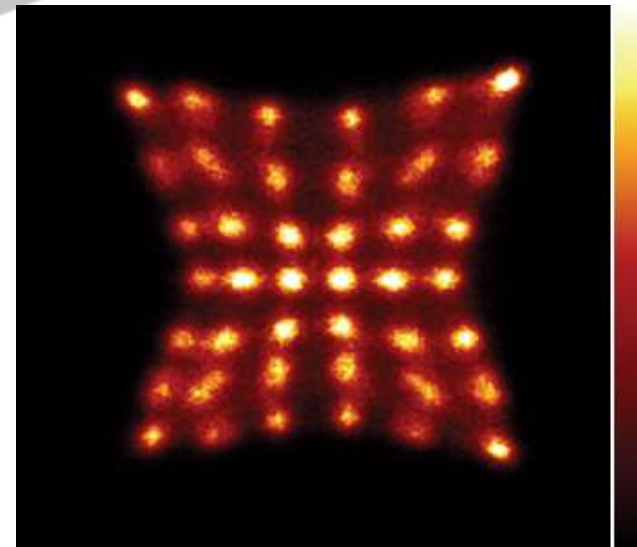
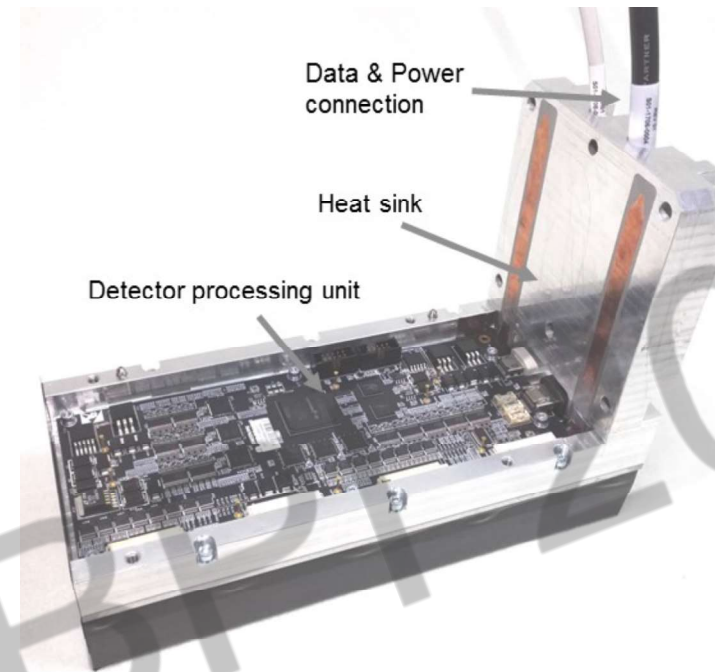
- 8 detector rings (**194 cm AFOV**)
- 24 detector modules per ring
- Up to 5 rings in coincidence axially ( $57^\circ$  maximum acceptance angle)
- Coincidence time window: 4.5 ns – 6.9 ns (ring difference dependent)
- ULD: 645 keV; LLD: 430 keV
- 565,480 crystals
- 53,760 SiPMs
- $\sim 91 \times 10^9$  lines-of-response



# Detector modules

Crystals: 2.76 x 2.76 x 18.1 mm LYSO  
SiPMs: 4 per block - SensL 6 mm J-series  
Block: 7 crystals (transaxial) x 6 (axial)  
Module: 5 (transaxial) x 14 (axial) blocks

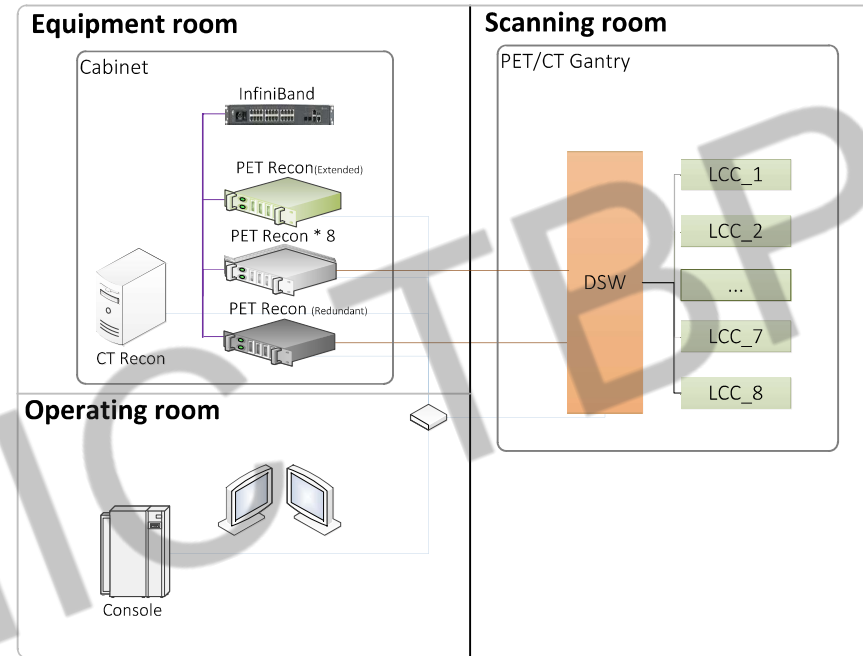
*Energy resolution: 11.7% @ 511keV*  
*Timing resolution: 430 ps*



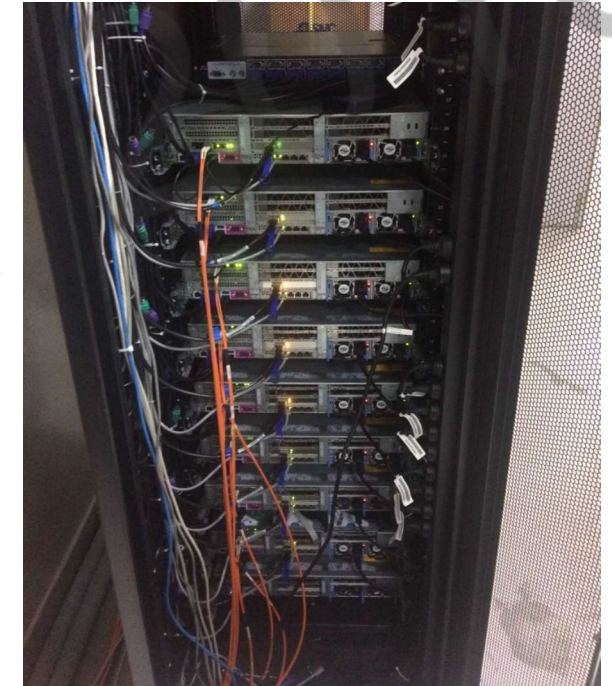
# Image reconstruction and data handling

- 8 ACQ&Recon nodes
- Scalable Recon nodes for only reconstruction
- Infiniband network: 36 FDR (56Gb/s) ports, 4Tb/s
- MPI paralleled reconstruction framework (listmode OSEM with TOF+PSF)

Component	Description	QTY
CPU	Intel Xeon 6126	2
Memory	16GB DDR4 ECC REG 2133	6
System disk	1T SATA enterprise-level hard disk	1
Data disk	Intel SSD P4600 2T	2
GPU	NVIDIA TESLA PCI-E P100(16GB)	2



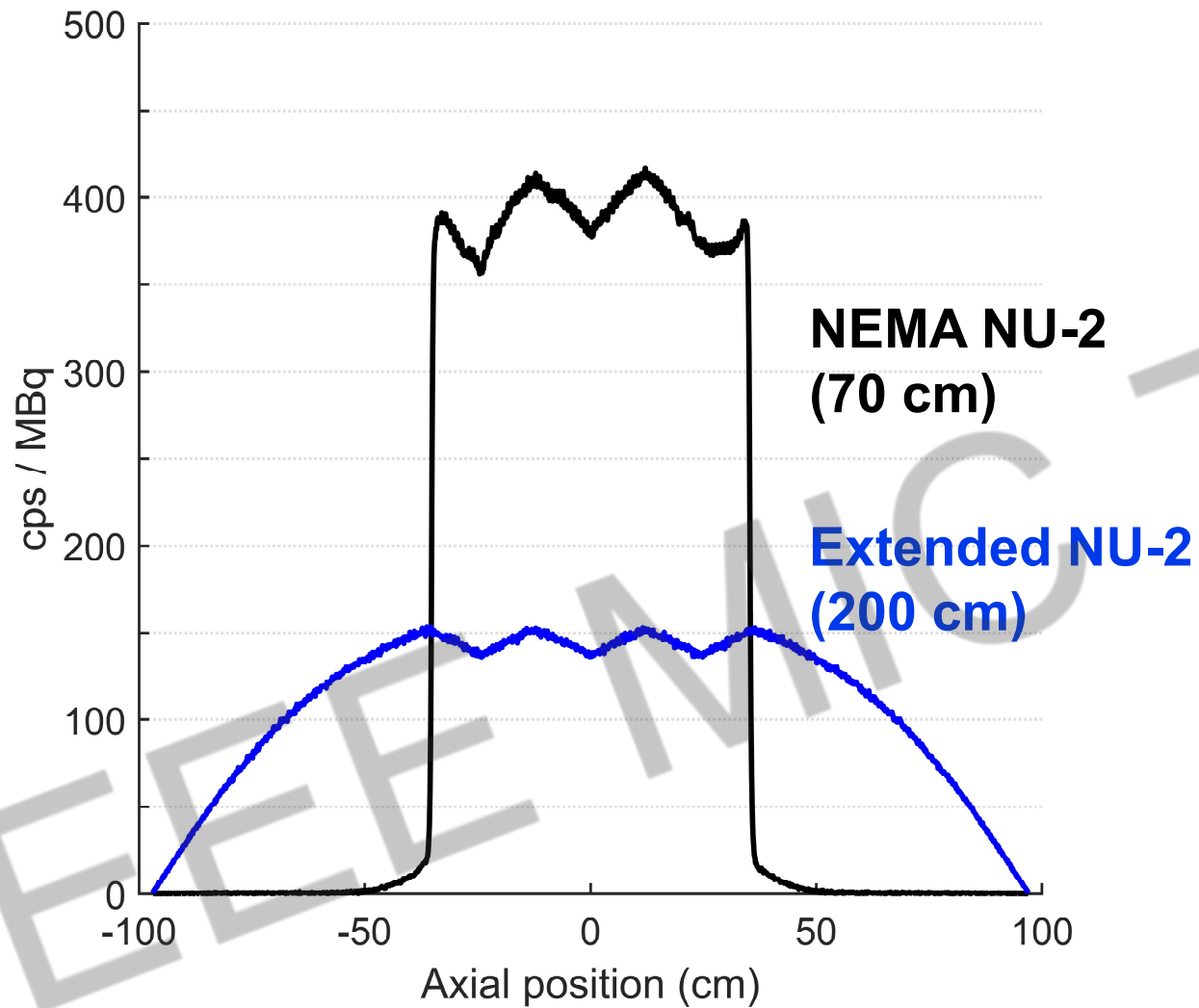
Reconstruction cluster



- Data volume: 20 min scan with ~7 mCi: **~18 billion prompts + delays, ~150 GB**
- Reconstruction time: 600 mm transaxial FOV; 3.2 mm pixels; 20 subsets, 3 iterations: **13 mins recon time**



# Sensitivity



NU-2 sensitivity

*Total at 0 cm: 191.5 kcps/MBq*

*Total at 10 cm: 193.9 kcps/MBq*

Extended NU-2 sensitivity

*Total at 0 cm: 151.0 kcps/MBq*

*Total at 10 cm: 153.1 kcps/MBq*

*See poster by Y. Zhao, et al. for more details.*



# Count rate performance

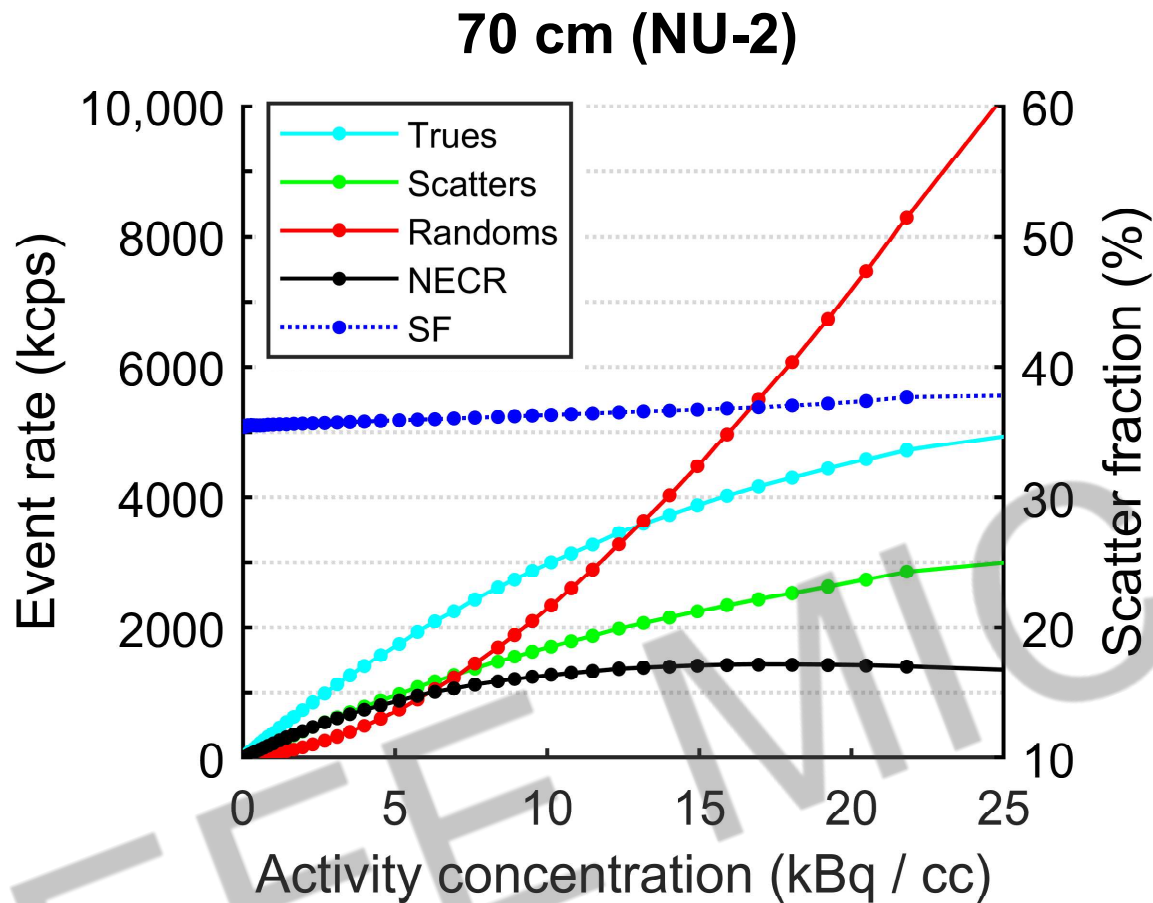


Compare two scatter phantom lengths  
(20 cm diameter):

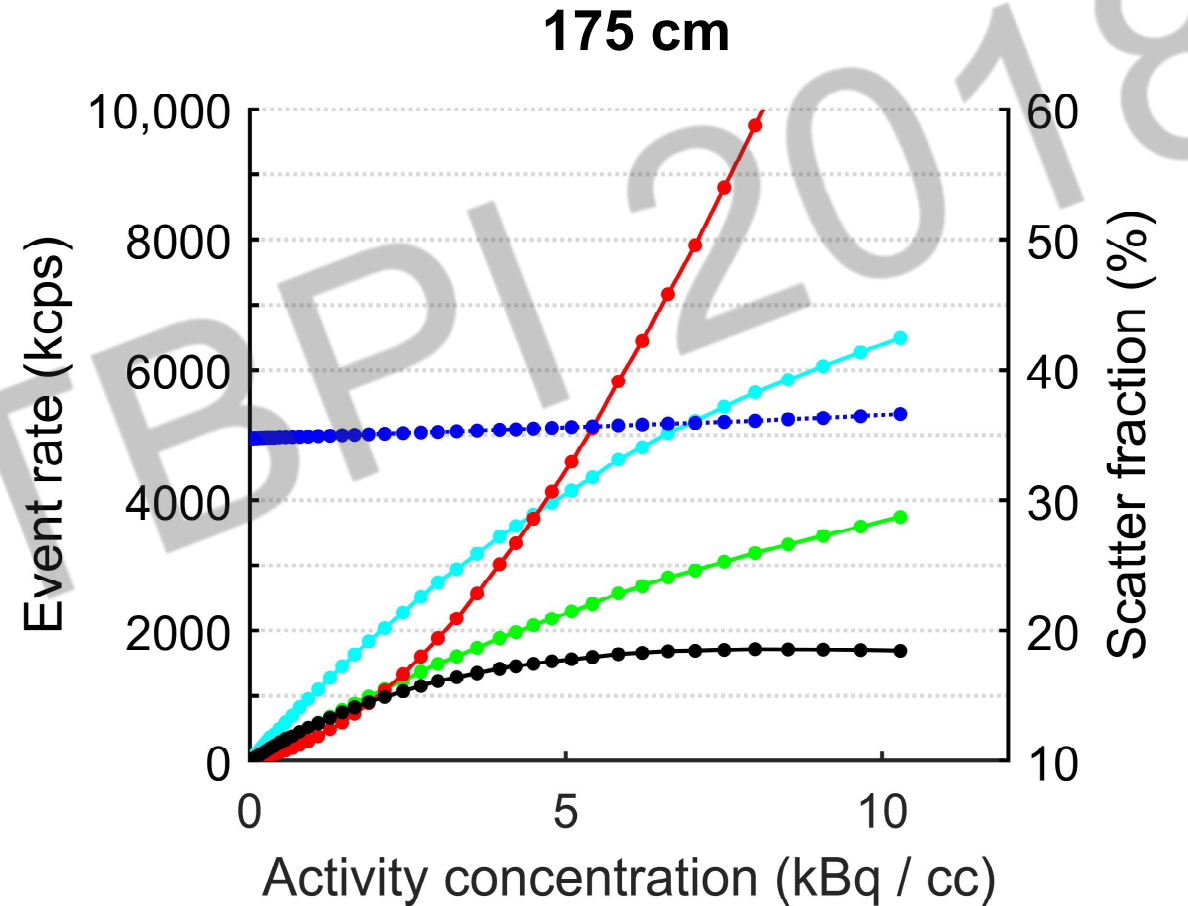
- 1) 70 cm (NEMA NU-2)
- 2) 175 cm (approximate human)

Both filled with  $\sim 25$  mCi  $^{18}\text{F}$ -FDG at the start of acquisitions.

# Count rate performance

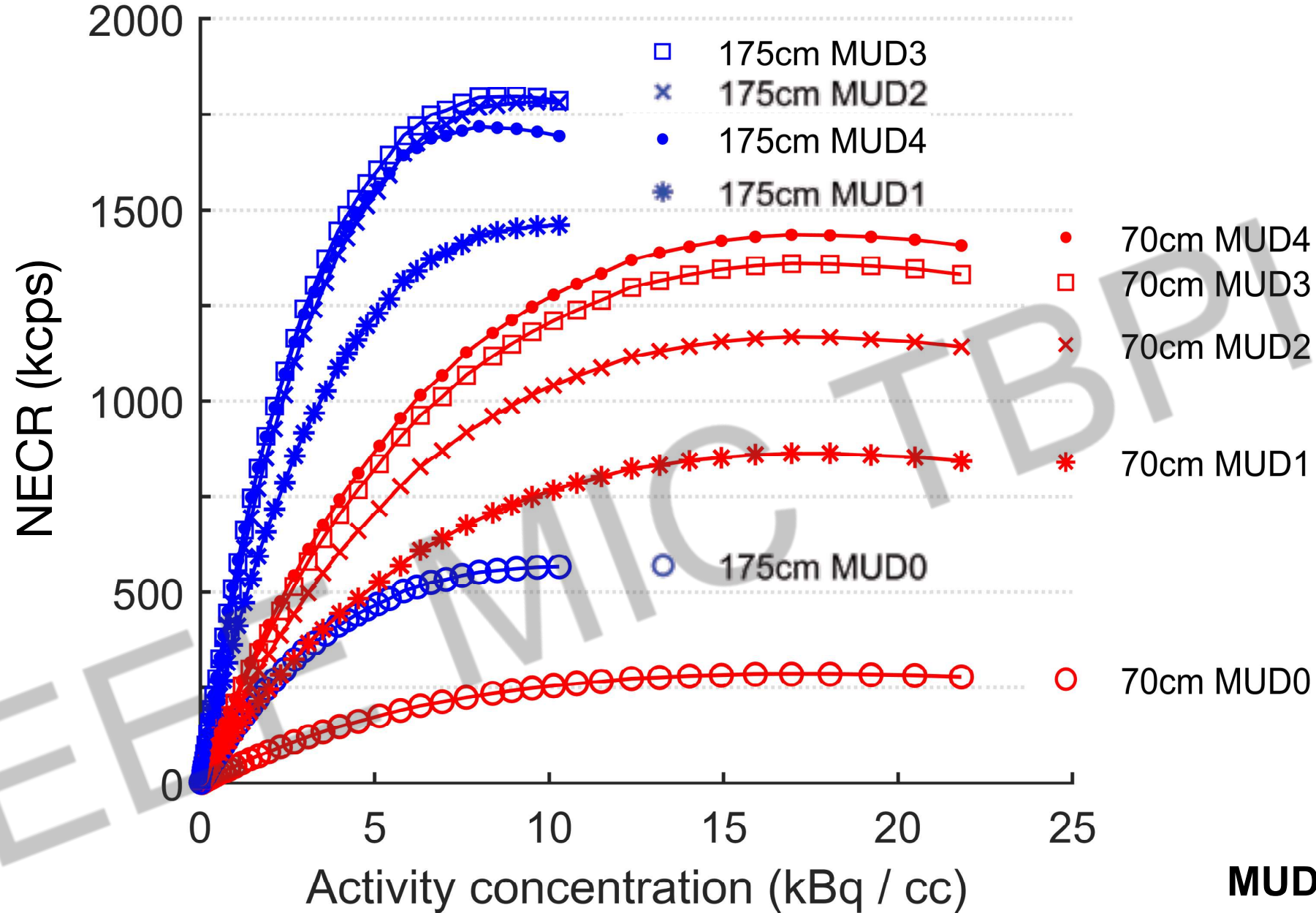


**Peak NECR: 1435 kcps @ 16.8 kBq/cc**  
**SF: 35.8% (up to peak NECR)**



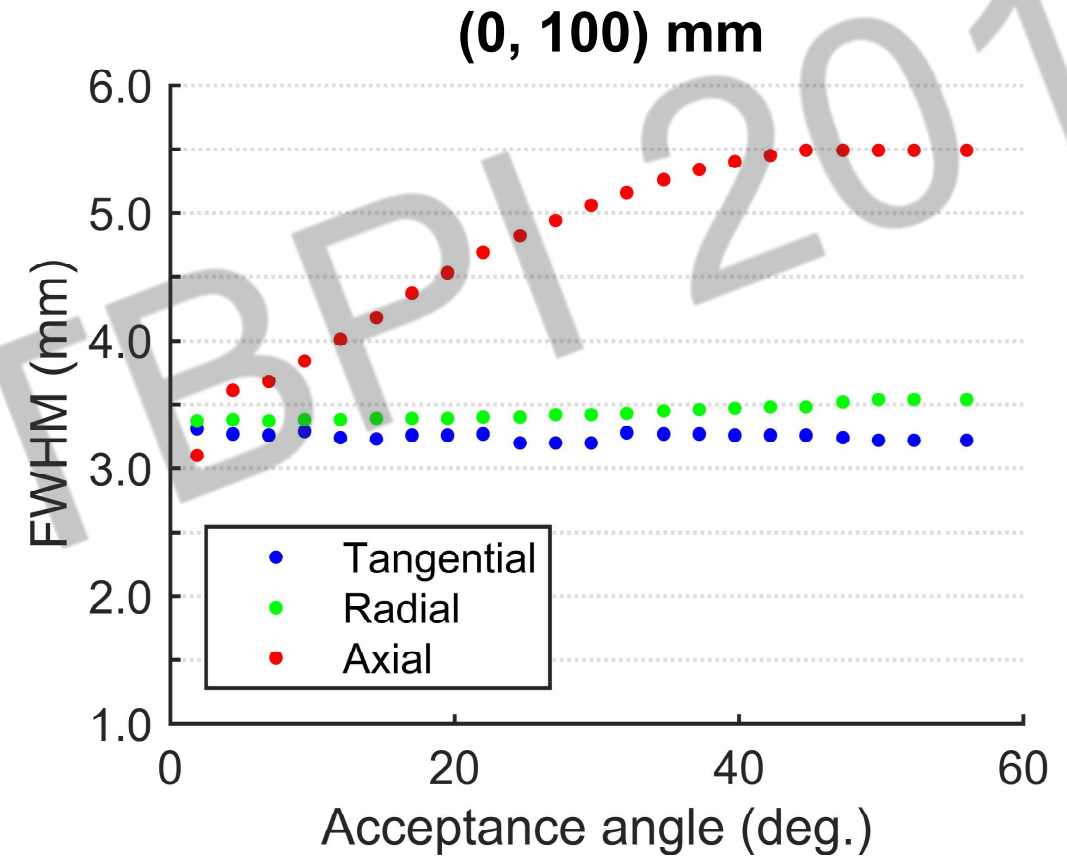
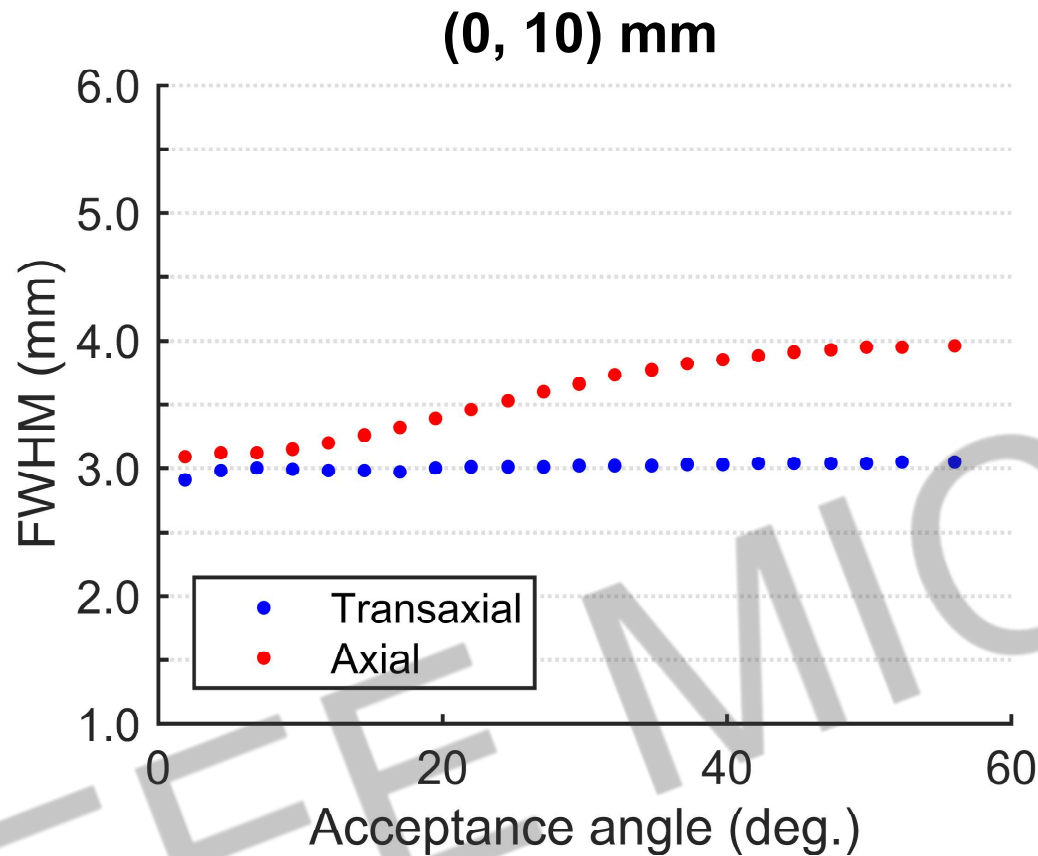
**Peak NECR: 1718 kcps @ 8.0 kBq/cc**  
**SF: 35.1% (up to peak NECR)**

# Effect of acceptance angle on NECR



**MUD:** *Maximum Unit Difference*

# Spatial resolution: NEMA NU-2

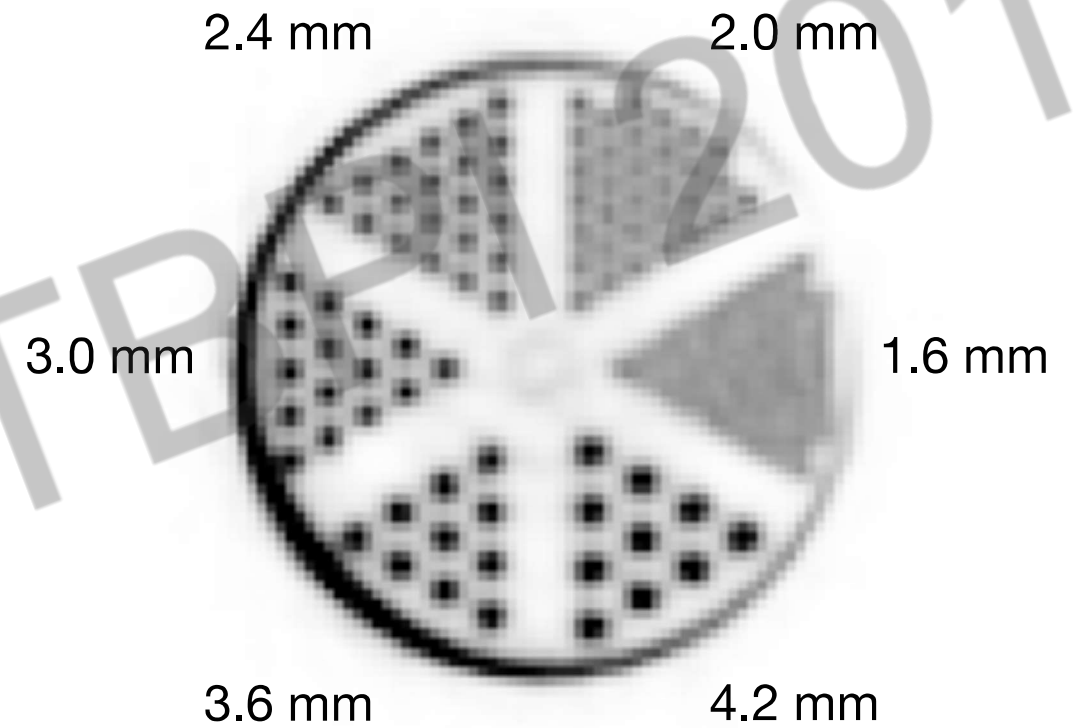
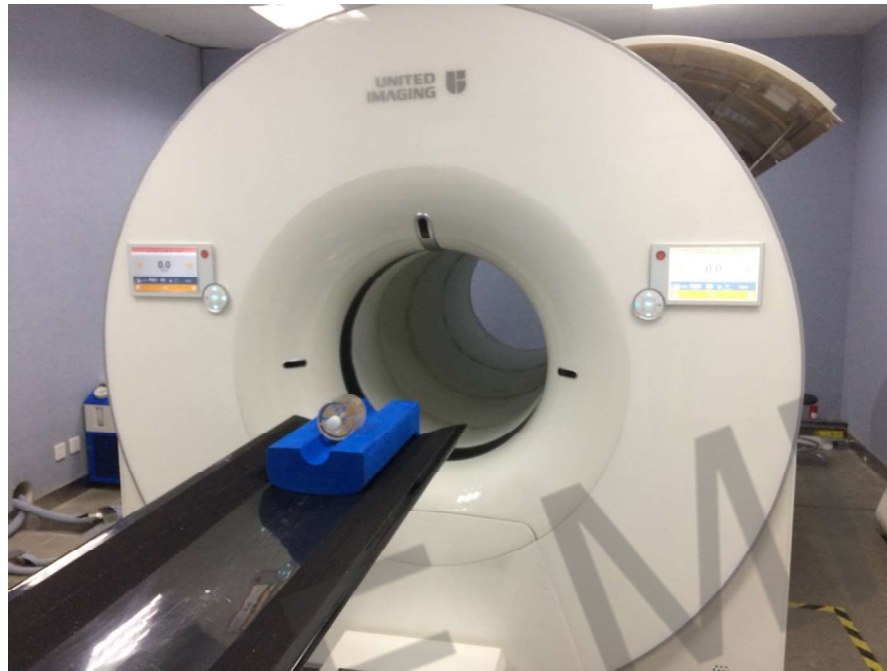


Reconstruction: FORE + 2DFBP  
Voxel size: 0.6 x 0.6 x 0.6 mm

*Future: reconstructed point source in a warm background (OSEM + PSF)*



# Spatial resolution: mini-Derenzo phantom

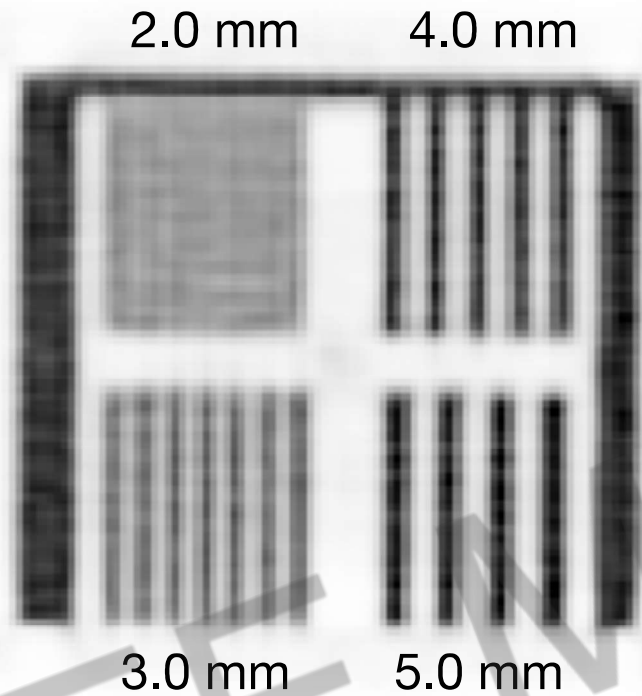


Transaxial slice.

8 billion total prompts.

Voxel size: 1.2 x 1.2 x 1.425 mm.

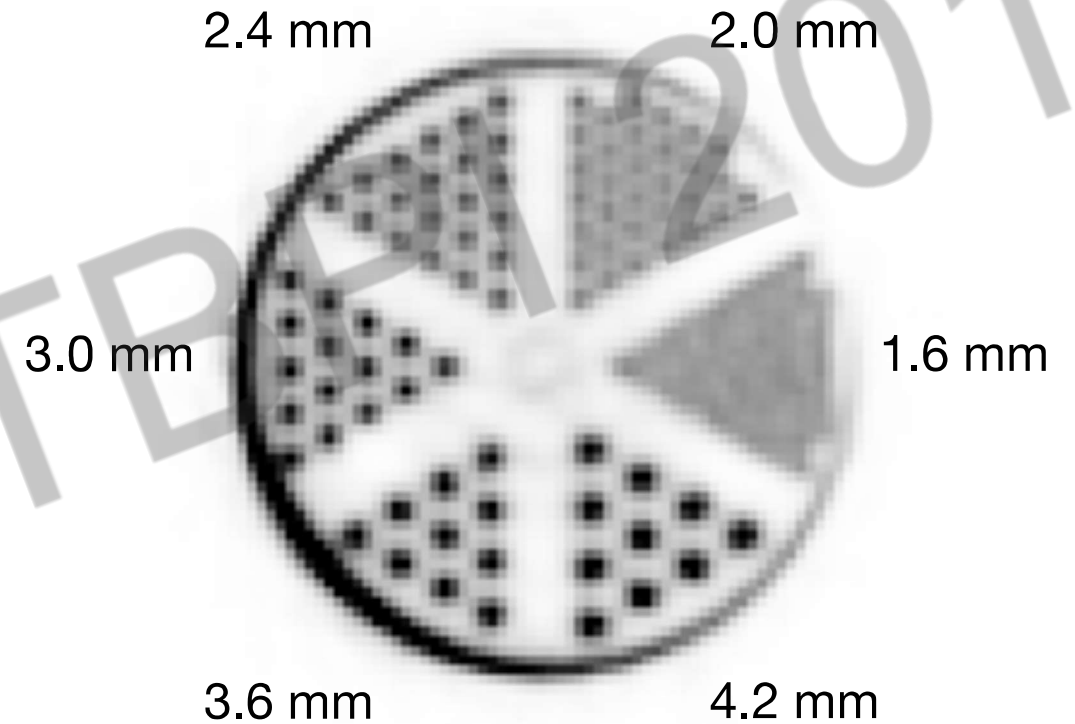
# Spatial resolution: Axial bar phantom



Sagittal slice.

12 billion total prompts.

Voxel size: 1.2 x 1.2 x 1.425 mm.

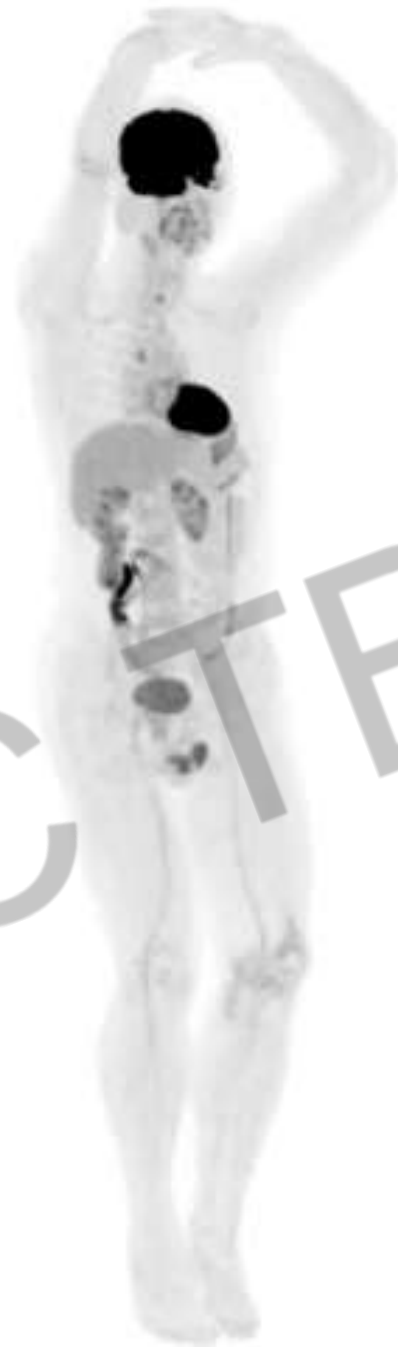


Transaxial slice.

8 billion total prompts.

Voxel size: 1.2 x 1.2 x 1.425 mm.

# First human images



1 minute acquisition!

61-yo male, 65 kg; 164 cm; 7.8 mCi; 82 min p.i.  
Credit: Zhongshan Hospital; Shanghai

# First human images



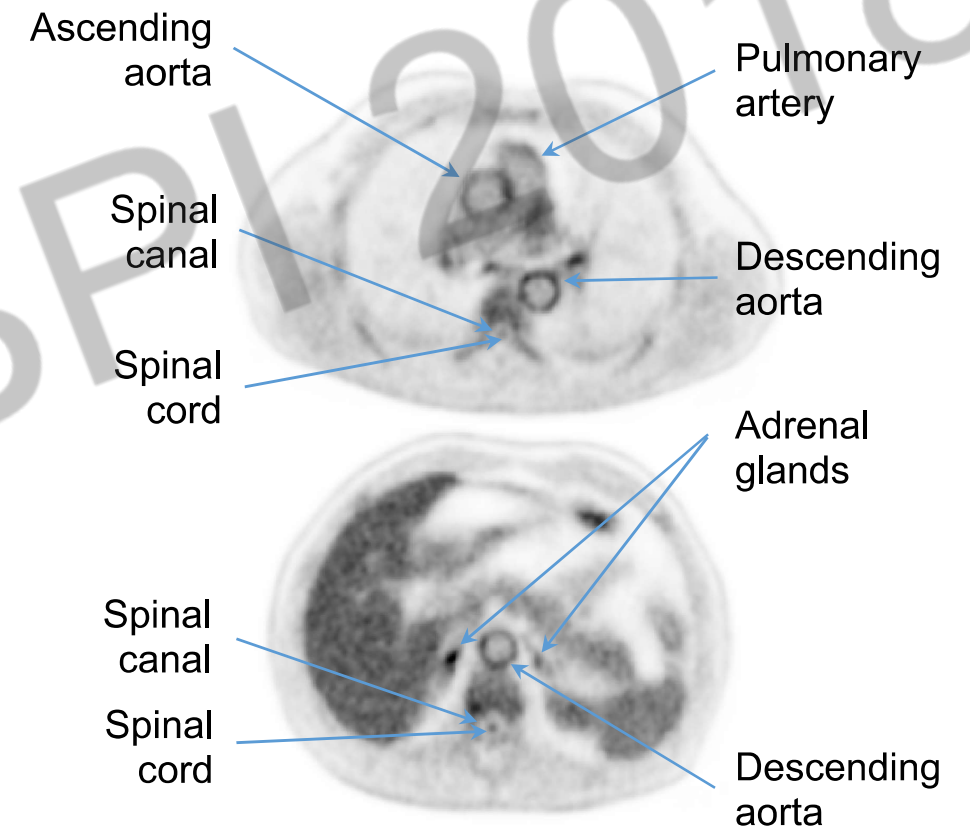
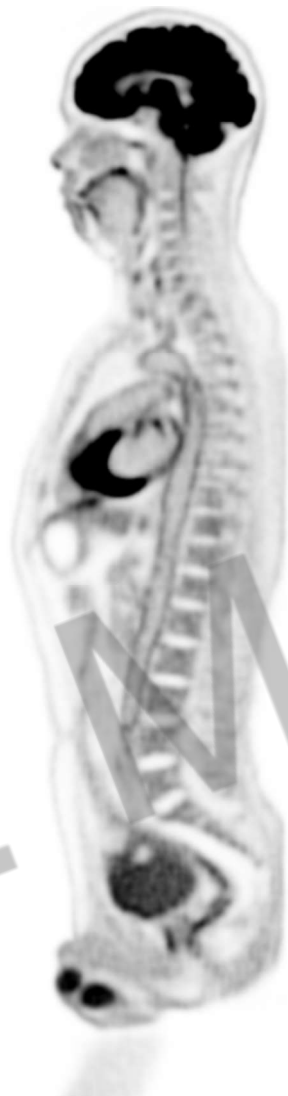
20 minute acquisition

61-yo male, 65 kg; 164 cm; 7.8 mCi; 82 min p.i.  
Credit: Zhongshan Hospital; Shanghai

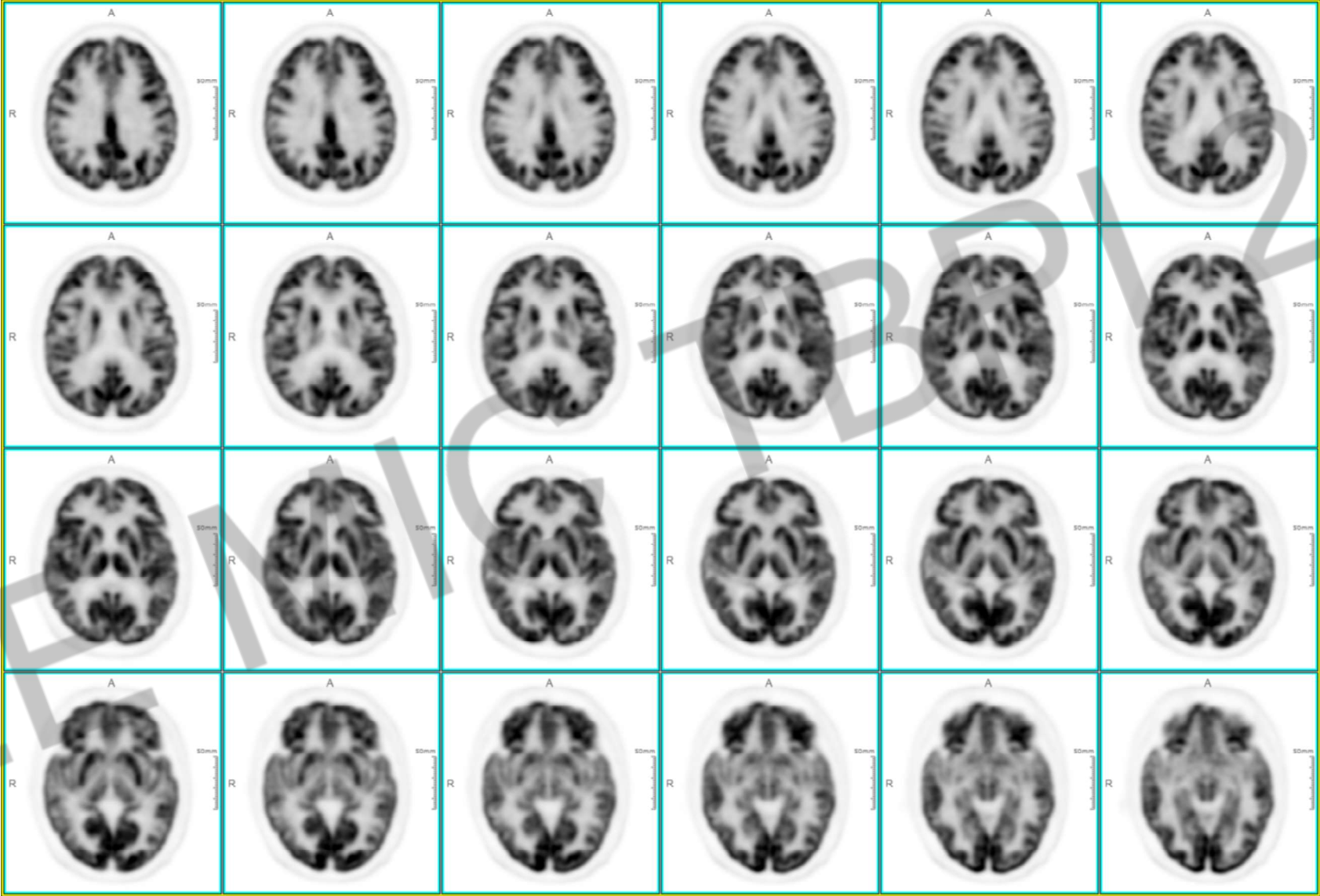


# First human images

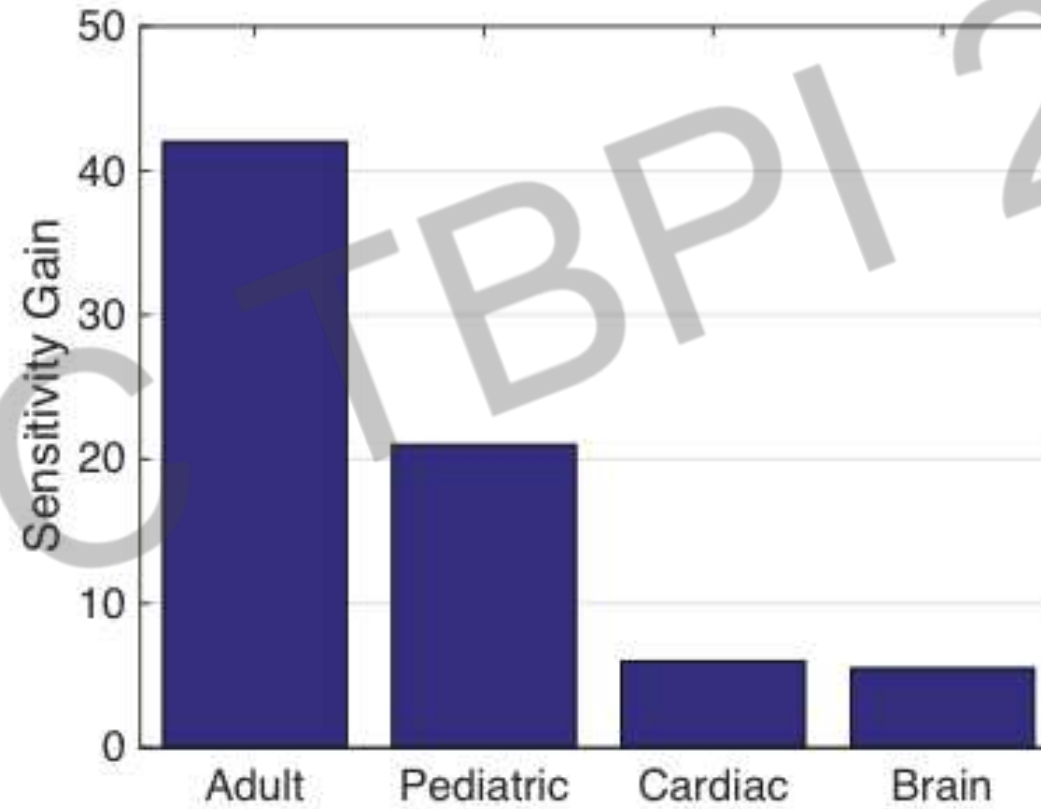
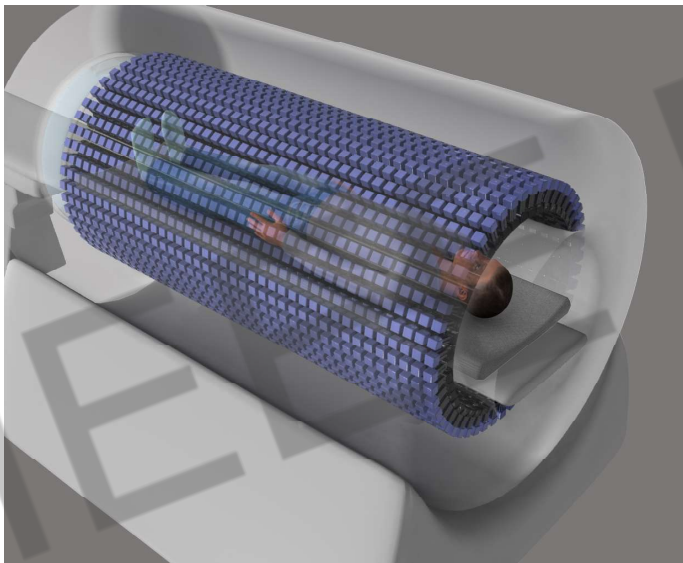
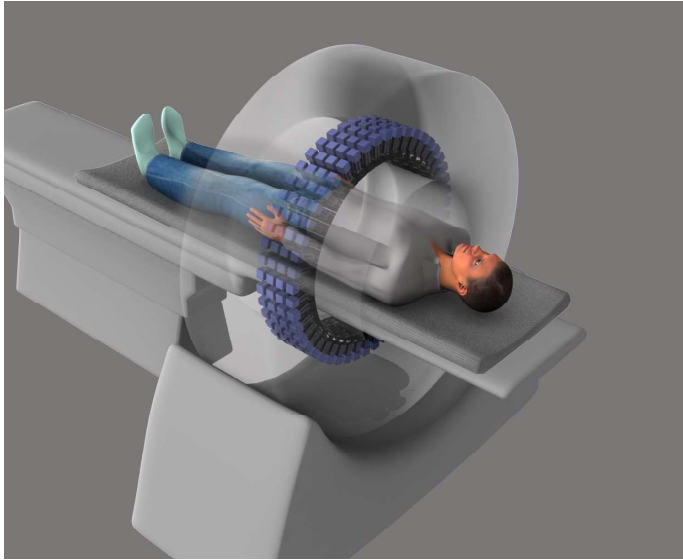
20 min acquisition,  
5 iterations,  
1 x 1 x 1.425 mm voxels



# First human images

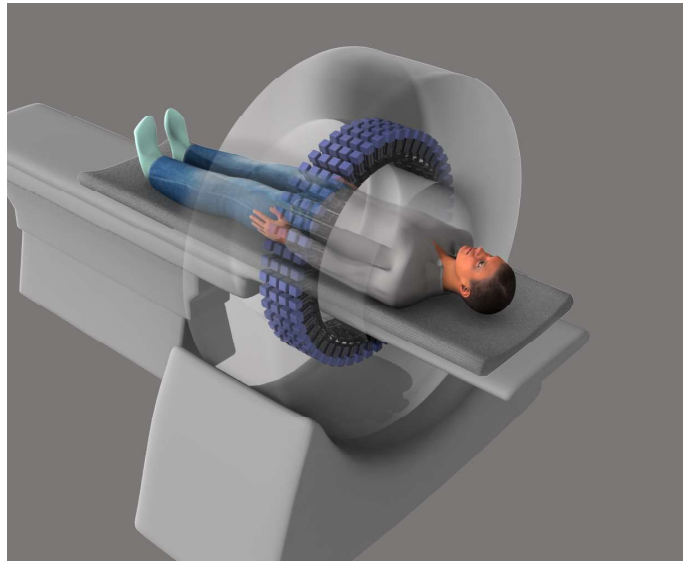


# EXPLORER claims



Jonathan Poon

# EXPLORER claims

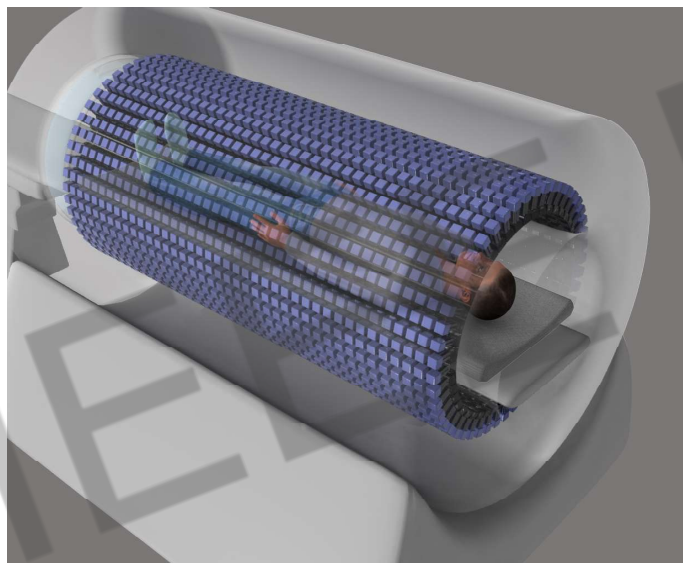


## Image better

- > 6-fold increase in SNR
- Reconstruct at higher resolution
- Detect smaller lesions
- Detect low-grade disease
- Better statistics for kinetic modeling

## Image faster

- Total-body PET in 15-30 secs
- Image in a single breath hold
- Reduce respiratory motion
- Higher resolution
- Total-body kinetic imaging with good temporal resolution



## Image longer

- 40-fold increase in dynamic range
- Image for 5 more half lives
- $^{11}\text{C}$  > 3 hours
- $^{18}\text{F}$  > 18 hours
- $^{89}\text{Zr}$  > 30 days

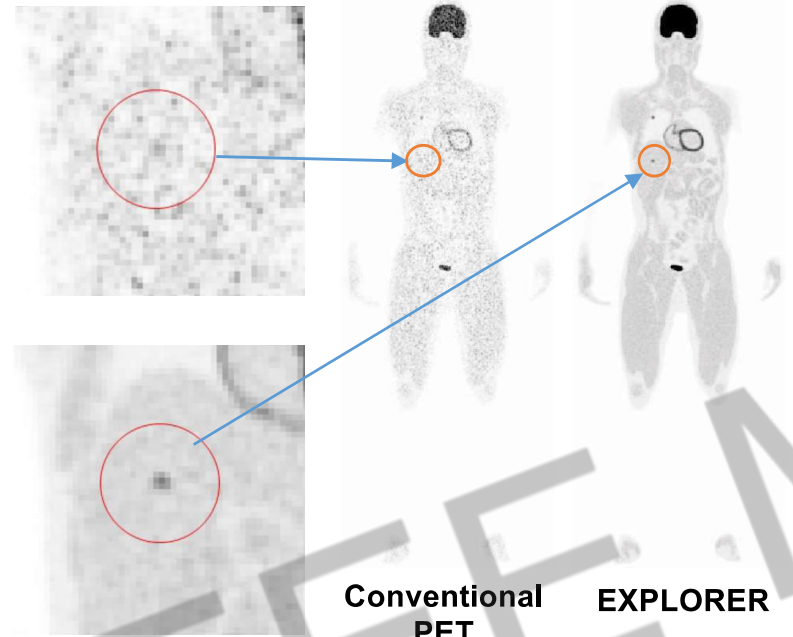
## Image gently

- 40-fold reduction in dose
- Whole-body PET at  $150\ \mu\text{Sv}$
- PET in new populations (adolescents, pediatrics)
- Many repeat scans in an individual (follow disease trajectory)



# Image better

- Reconstruct at higher resolution
- Detect smaller lesions



Conventional PET      EXPLORER

Courtesy of Dr. Xuezhu Zhang

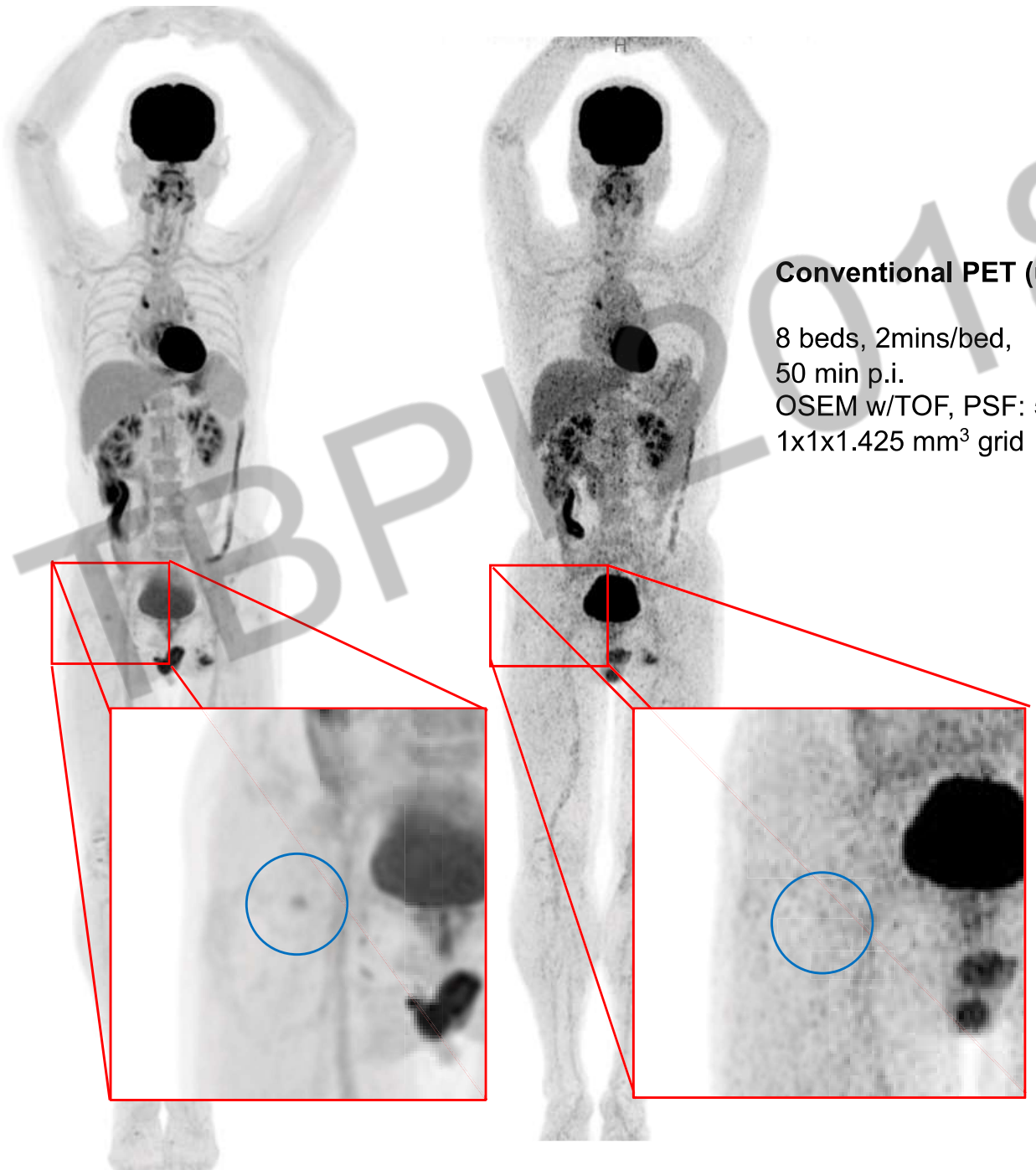
61-yo male, 65 kg; 164 cm; 7.8 mCi  
Credit: Zhongshan Hospital; Shanghai

## EXPLORER

20 min scan, 1 bed  
82 min p.i.  
OSEM w/TOF, PSF: 5i 20s  
1x1x1.425 mm<sup>3</sup> grid

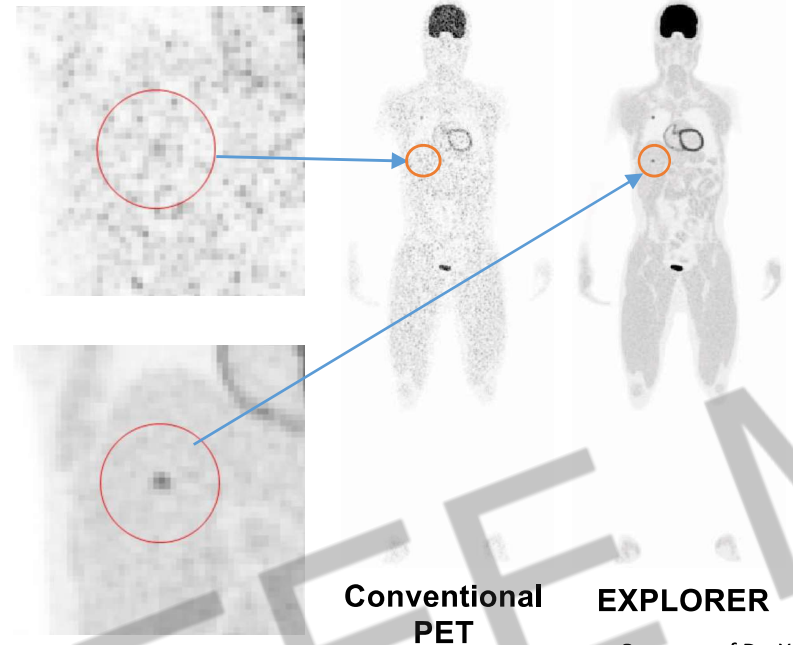
## Conventional PET (uMI780)

8 beds, 2mins/bed,  
50 min p.i.  
OSEM w/TOF, PSF: 5i 20s  
1x1x1.425 mm<sup>3</sup> grid



# Image better

- Reconstruct at higher resolution
- Detect smaller lesions



**Conventional PET**      **EXPLORER**

Courtesy of Dr. Xuezhu Zhang

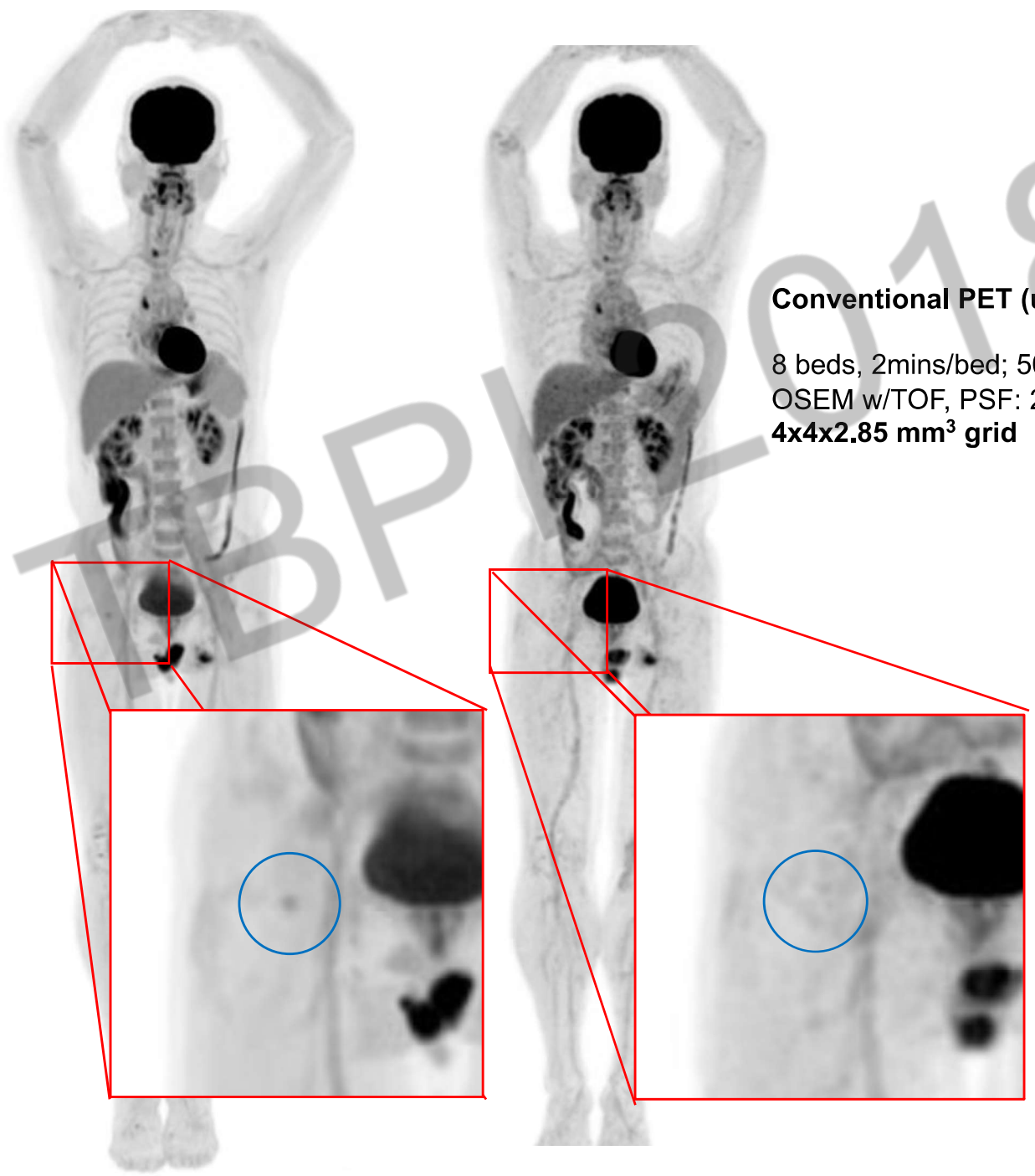
61-yo male, 65 kg; 164 cm; 7.8 mCi  
Credit: Zhongshan Hospital; Shanghai

## EXPLORER

20 min scan, 1 bed; 82 min p.i.  
OSEM w/TOF, PSF: 2i 20s  
4x4x2.85 mm<sup>3</sup> grid

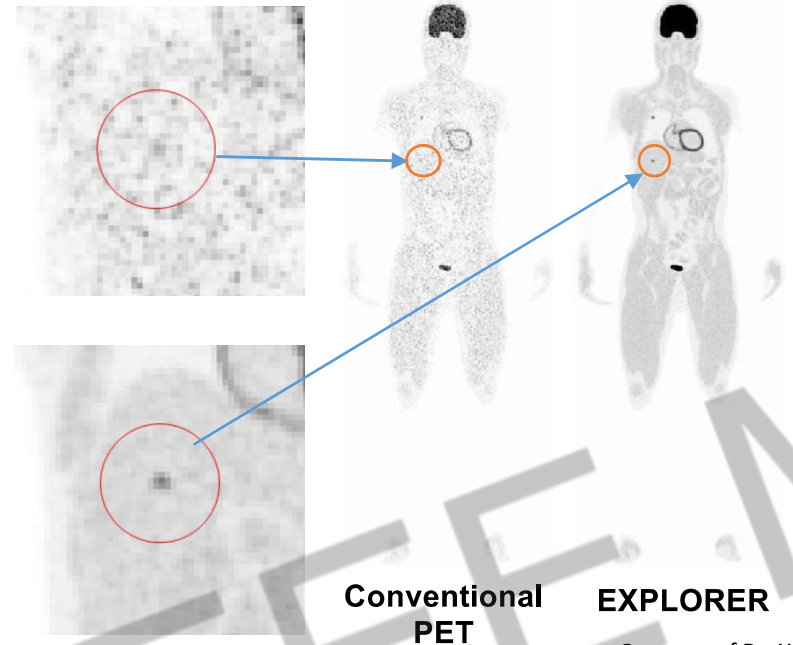
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4x4x2.85 mm<sup>3</sup> grid



# Image better

- Reconstruct at higher resolution
- Detect smaller lesions



Conventional PET      EXPLORER

Courtesy of Dr. Xuezhu Zhang

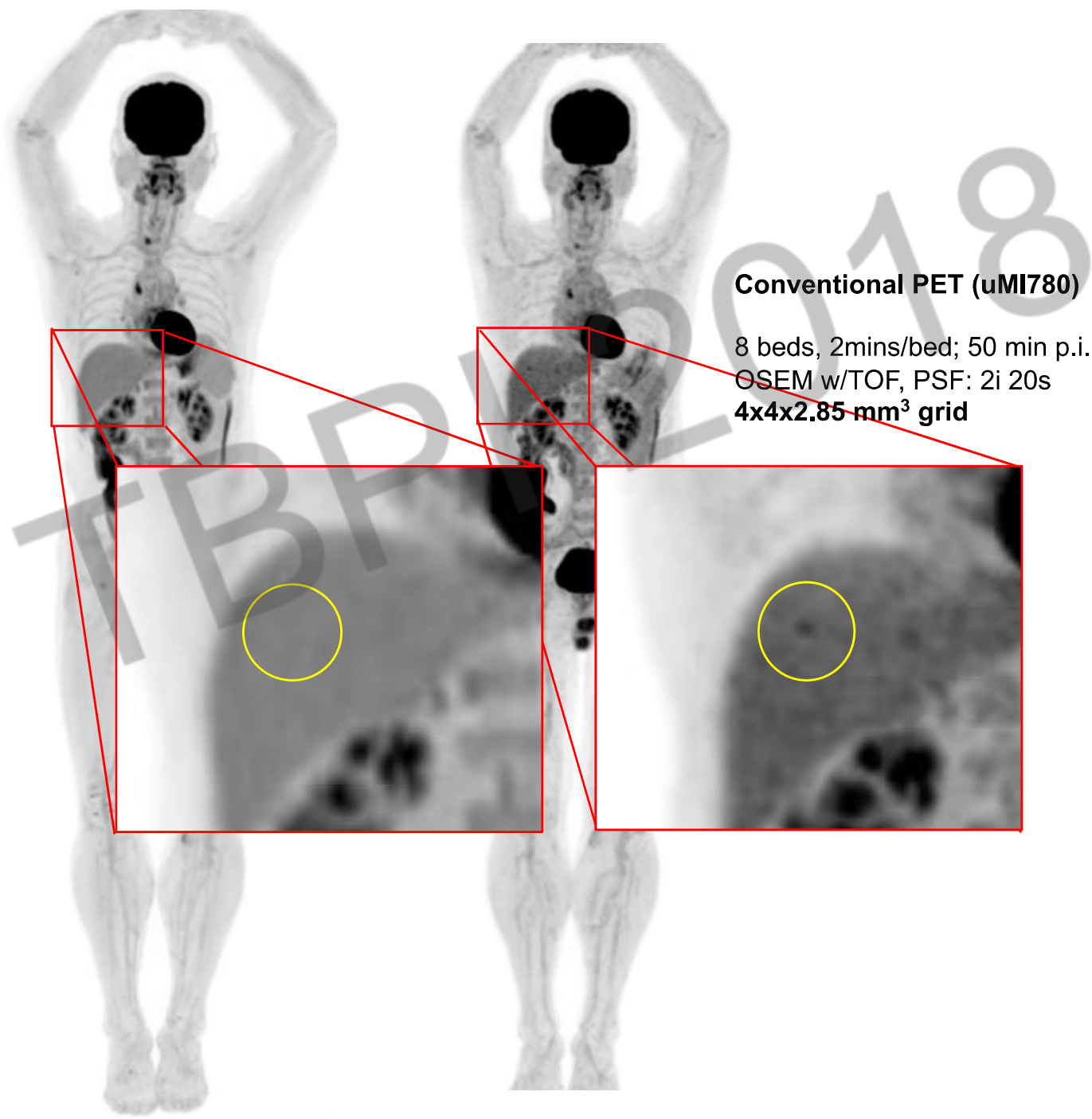
61-yo male, 65 kg; 164 cm; 7.8 mCi  
Credit: Zhongshan Hospital; Shanghai

## EXPLORER

20 min scan, 1 bed; 82 min p.i.  
OSEM w/TOF, PSF: 2i 20s  
4x4x2.85 mm<sup>3</sup> grid

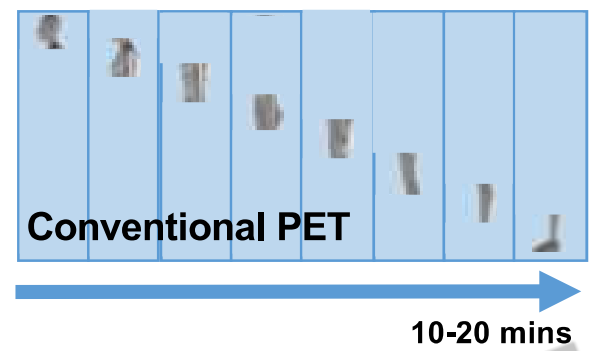
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OSEM w/TOF, PSF: 2i 20s  
4x4x2.85 mm<sup>3</sup> grid



# Image faster

- Total-body PET in 15-30 secs
- Reduce respiratory motion
- Higher resolution



20 min



10 min



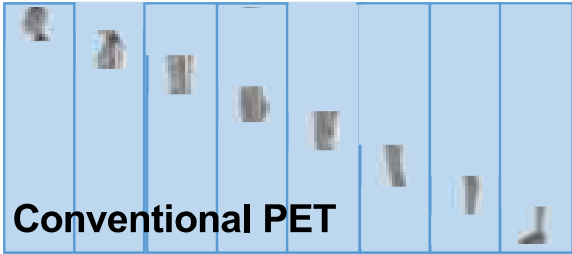
uMI 780

61-yo male, 65 kg; 164 cm; 7.8 mCi; 82 min p.i.; 20 min acq.  
Credit: Zhongshan Hospital; Shanghai



# Image faster

- Total-body PET in 15-30 secs
- Reduce respiratory motion
- Higher resolution



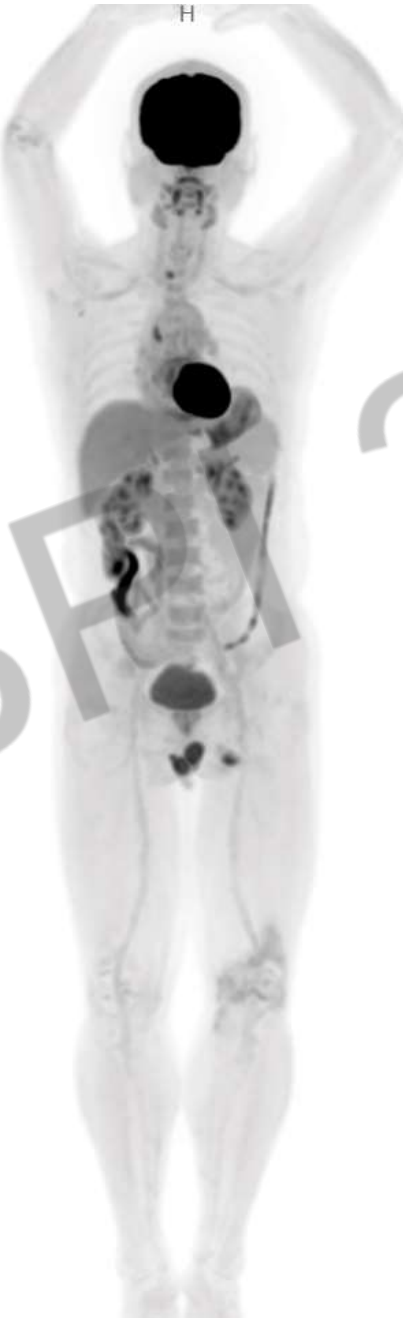
10-20 mins



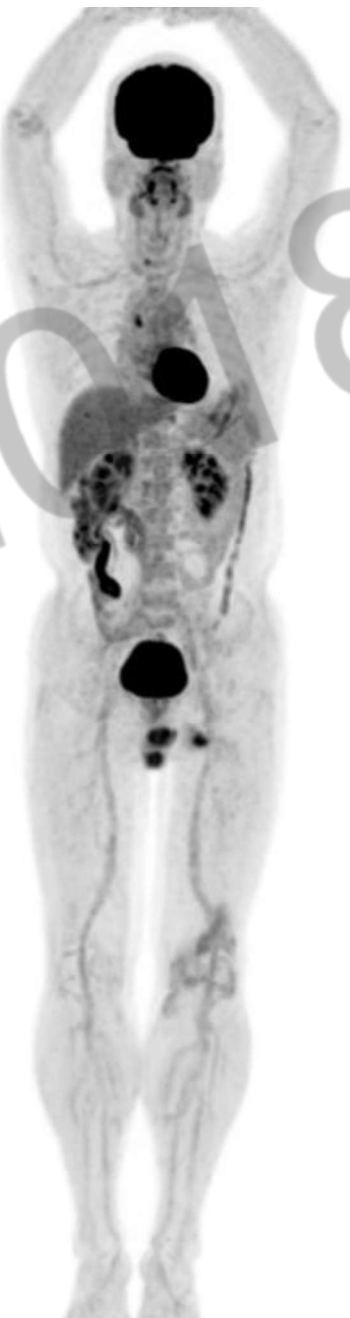
EXPLORER  
30 seconds



20 min



5 min

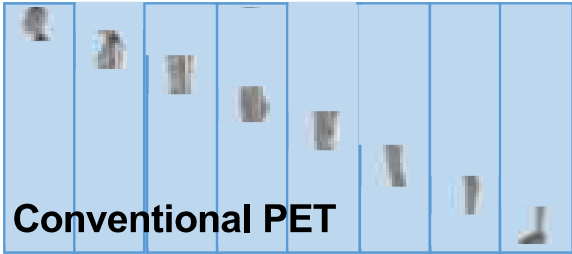


uMI 780

61-yo male, 65 kg; 164 cm; 7.8 mCi; 82 min p.i.; 20 min acq.  
Credit: Zhongshan Hospital; Shanghai

# Image faster

- Total-body PET in 15-30 secs
- Reduce respiratory motion
- Higher resolution



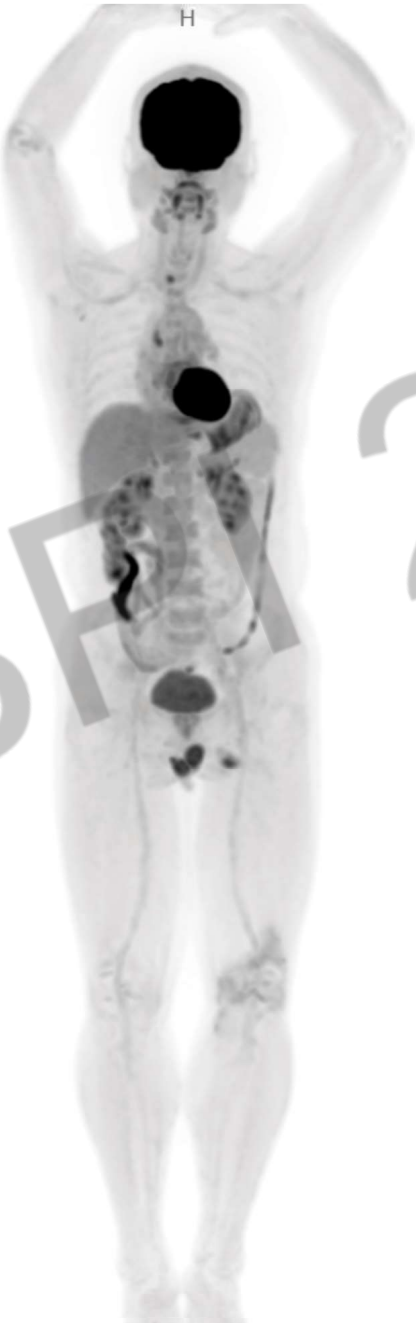
10-20 mins



EXPLORER  
30 seconds



20 min



2 min

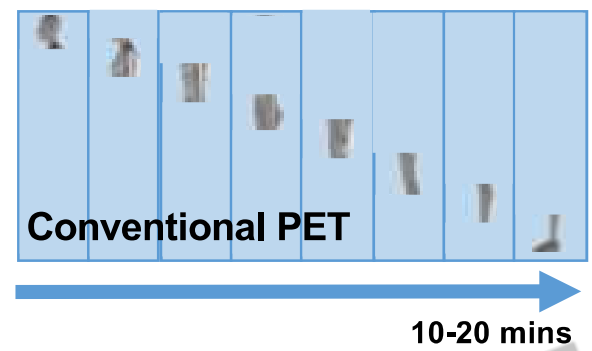


uMI 780

61-yo male, 65 kg; 164 cm; 7.8 mCi; 82 min p.i.; 20 min acq.  
Credit: Zhongshan Hospital; Shanghai

# Image faster

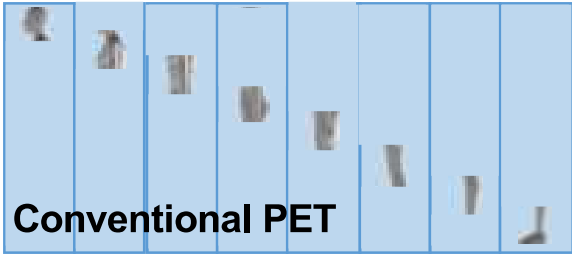
- Total-body PET in 15-30 secs
- Reduce respiratory motion
- Higher resolution



61-yo male, 65 kg; 164 cm; 7.8 mCi; 82 min p.i.; 20 min acq.  
Credit: Zhongshan Hospital; Shanghai

# Image faster

- Total-body PET in 15-30 secs
- Reduce respiratory motion
- Higher resolution



10-20 mins



EXPLORER  
30 seconds



20 min



37.5 sec



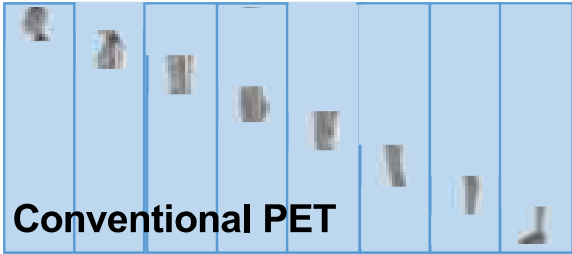
uMI 780

61-yo male, 65 kg; 164 cm; 7.8 mCi; 82 min p.i.; 20 min acq.  
Credit: Zhongshan Hospital; Shanghai



# Image faster

- Total-body PET in 15-30 secs
- Reduce respiratory motion
- Higher resolution



10-20 mins



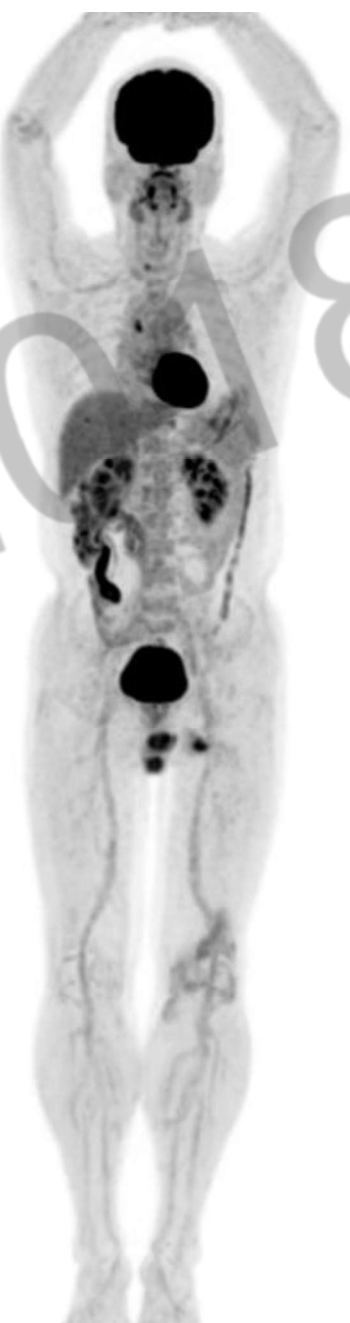
EXPLORER  
30 seconds



20 min



18.75 sec



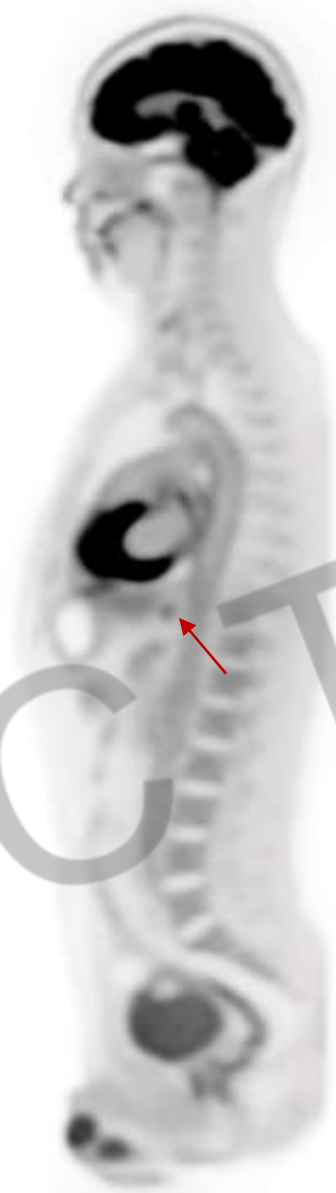
uMI 780

61-yo male, 65 kg; 164 cm; 7.8 mCi; 82 min p.i.; 20 min acq.  
Credit: Zhongshan Hospital; Shanghai

# Image faster

- Total-body PET in 15-30 secs
- Reduce respiratory motion
- Higher resolution

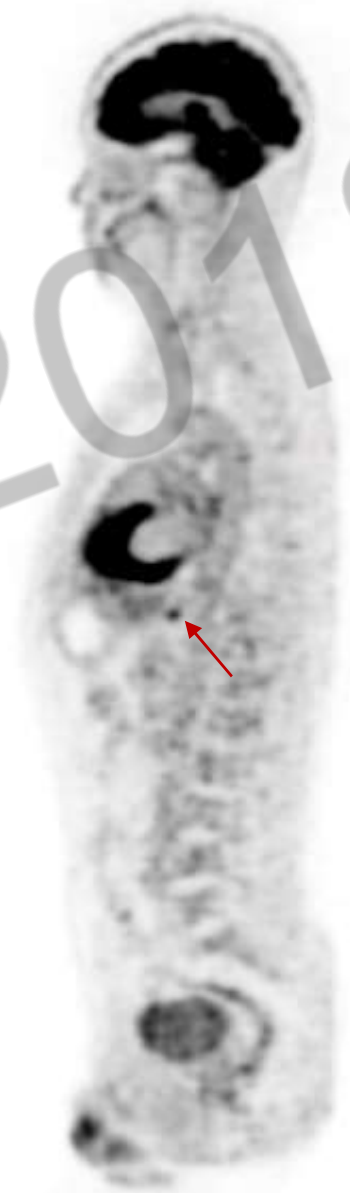
Effect of reduced respiratory blurring?  
Or noise artifact?



10 min



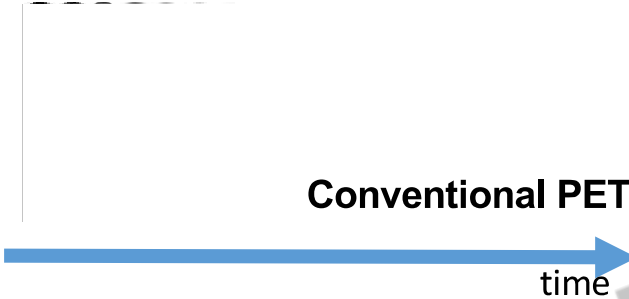
37.5 sec



18.75 sec

# Image longer

- Image for 5 more half lives
- Reveal kinetics inaccessible currently



EXPLORER

56 kg female; 6.7 mCi injected activity; 14 min acquisition



# Image longer:

## 30-day $^{89}\text{Zr}$ -antibody imaging with miniEXPLORER I

*Day 0: 60 minute dynamic scan*

*30 minute scans*

*45 min scan*

0-15 min.

15-30 min.

30-45 min.

45-60 min.

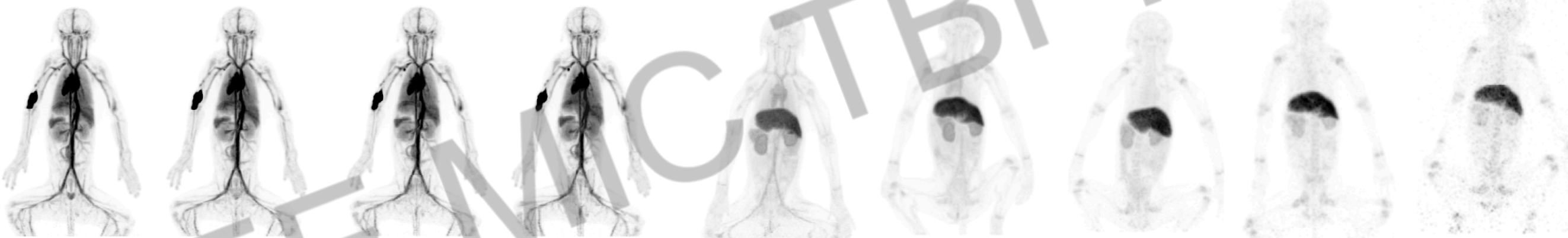
3 days

7 days

14 days

21 days

30 days



Rhesus monkey (2 yr, 2.1 kg)

1.1 mCi  $^{89}\text{Zr}$ -antibody injection + cold antibody on Day 0



# Low dose imaging

- 40-fold reduction in dose
- Whole-body PET at 150  $\mu$ Sv



Conventional PET



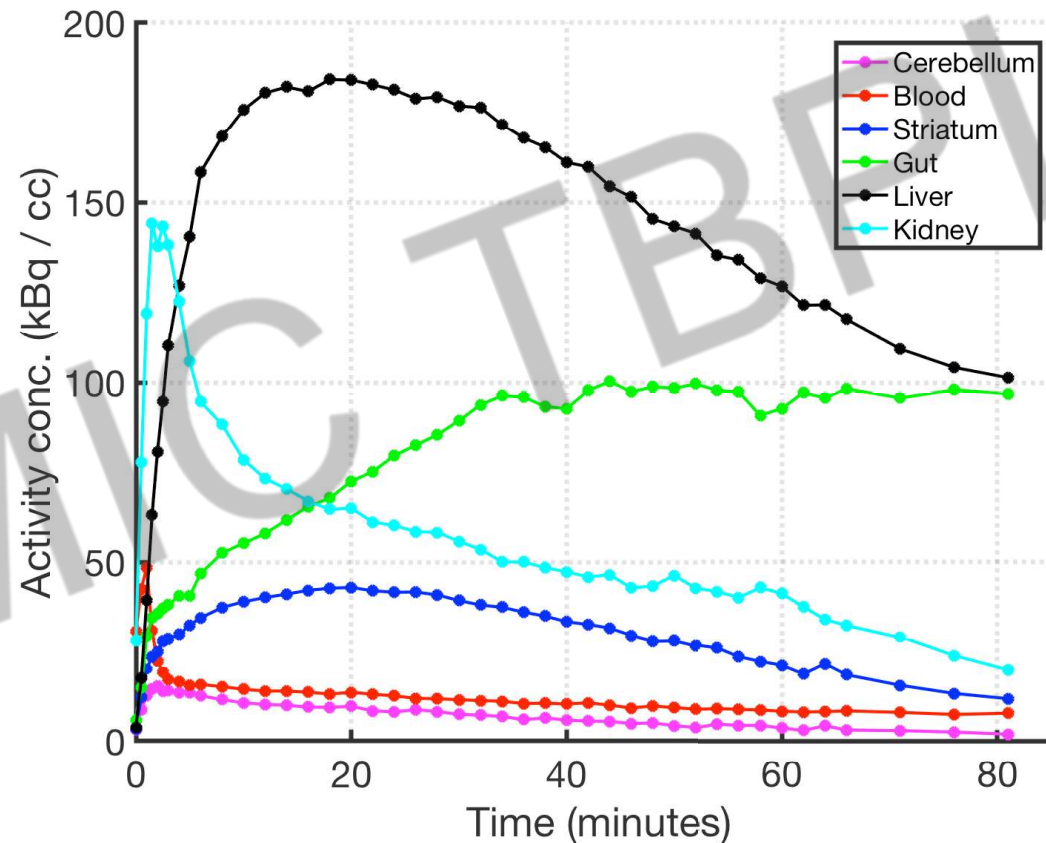
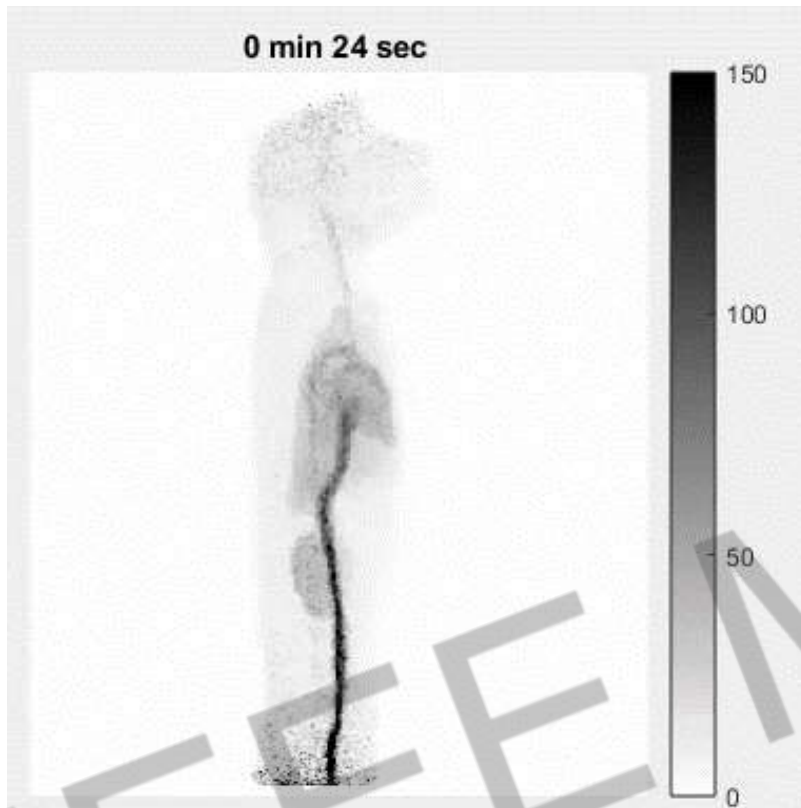
EXPLORER

44 kg female; 0.67 mCi injected FDG; 10 min acquisition; 50 min p.i.

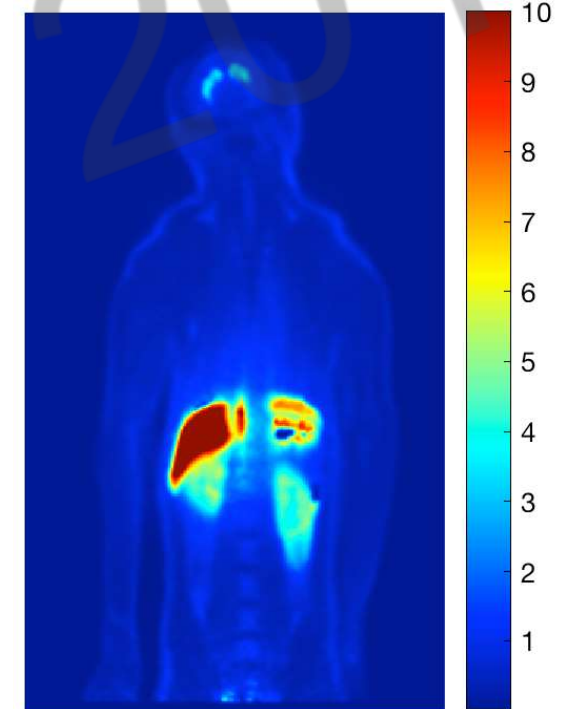


# Dynamic imaging of the whole body

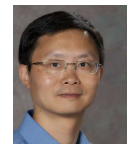
Total body kinetic modeling of  $^{11}\text{C}$ -raclopride in monkeys using miniEXPLORER I



Distribution Volume by Logan Plot

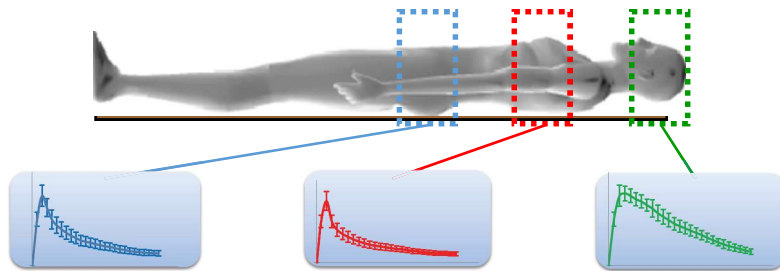


Liz Li



Guobao Wang

# Dynamic imaging of the whole body



Regional tissue kinetics & arterial blood input functions with high statistical quality.

Short dynamic frames.

# Summary

0 min 0 sec

uEXPLORER: first total-body scanner is built and preliminary healthy volunteer human studies completed.

Ongoing development of total-body imaging applications with miniEXPLORER systems.





# EXPLORER Program Acknowledgements



Simon Cherry  
Ramsey Badawi  
Terry Jones  
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Jonathan Poon  
Edwin Leung  
Xuezhu Zhang  
Liz Li  
Guobao Wang  
Brijesh Patel  
Alice Tarantal  
Cameron Foster  
Ed Ronningen  
Denise Caudle  
Matteo Bovio  
Jim Herod



William Moses  
Qiyu Peng



Joel Karp  
Suleman Surti  
Jeffrey Schmall  
Varsha Viswanath  
Michael Geagan

## Industrial collaborators:

United Imaging  
Siemens  
SensL  
Philips  
KAGE Medical

**Industry Advisory Panel:**  
Hongdi Li (United Imaging)  
Michael Casey (Siemens)  
Matthias Schmand (Siemens)  
Chi-Hua Tung (Philips)  
Chuck Stearns (GE)  
Gerd Muehllehner (KAGE)

## United Imaging engineering team:



## Funding:

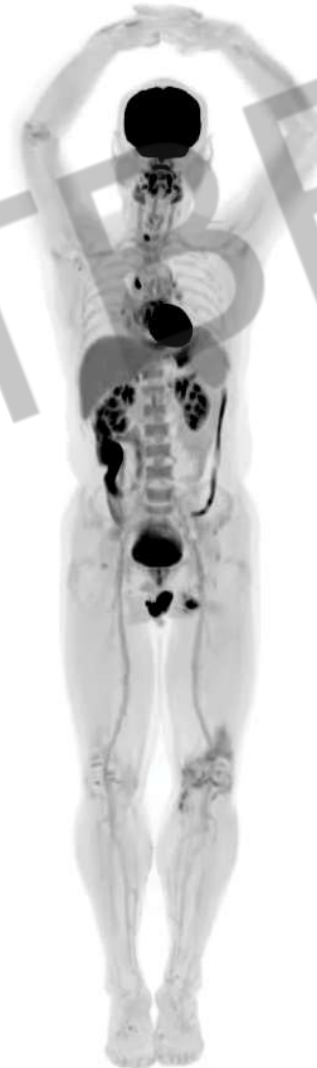
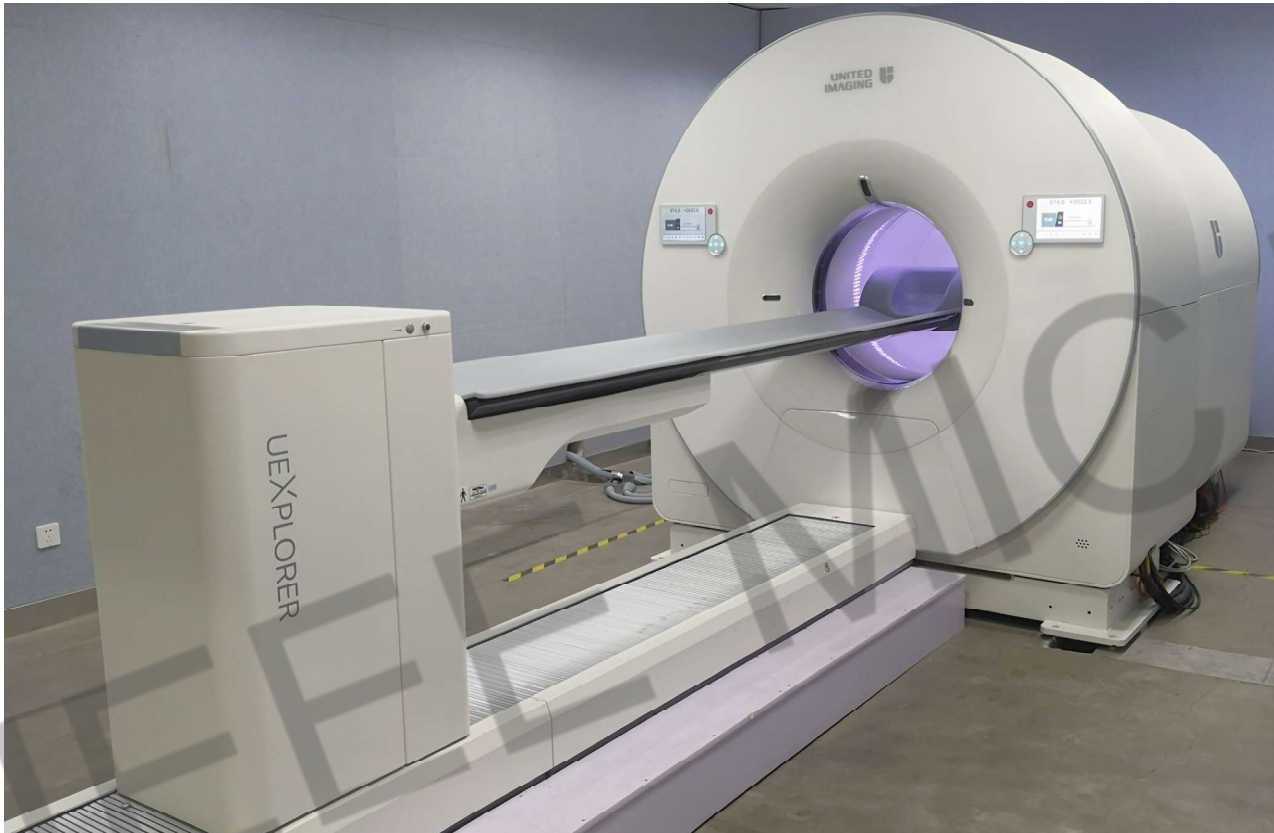
R01 CA170874  
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also supported by NIBIB and the Office  
of the Director  
R35 CA197608  
UC Davis and U Penn

## Medical Advisory Team

Richard Wahl (Washington Univ.)  
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Michael Graham (Univ. of Iowa)  
William Jagust (LBNL)  
Pat Price (Imperial College)  
Roger Gunn (Imanova)  
Ilan Rabiner (Imanova)

# Postdoctoral Positions

## *EXPLORER Total-Body PET Project*



Interested?

Send your CV to:

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Deadline: December 15th